SOLAR HEATING & COOLING PROGRAMME
INTERNATIONAL ENERGY AGENCY

New technologies and components for Solar Energy Buildings

IEA SHC TASK 66 | SOLAR ENERGY BUILDINGS

SHC TASK 66 Solar Energy Buildings

Technology Collaboration Programme
by iea

New technologies and components for Solar Energy Buildings

This is a report from SHC Task 66: Solar Energy Buildings and work performed in Subtask D: SEB Solution Sets

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Cover photo credit Jenni Energietechnik AG, 100% solar-heated multi-family building in Oberburg, Switzerland

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The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency.

Our mission is *"Through multi-disciplinary international collaborative research and knowledge exchange, as well as market and policy recommendations, the IEA SHC will work to increase the deployment rate of solar heating and cooling systems by breaking down the technical and non-technical barriers."*

IEA SHC members carry out cooperative research, development, demonstrations, and exchanges of information through Tasks (projects) on solar heating and cooling components and systems and their application to advance the deployment and research and development activities in the field of solar heating and cooling.

Our focus areas, with the associated Tasks in parenthesis, include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54, 69)
- Solar Cooling (Tasks 25, 38, 48, 53, 65)
- Solar Heat for Industrial and Agricultural Processes (Tasks 29, 33, 49, 62, 64)
- Solar District Heating (Tasks 7, 45, 55, 68)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56, 59, 63, 66)
- Solar Thermal & PV (Tasks 16, 35, 60)
- Daylighting/Lighting (Tasks 21, 31, 50, 61, 70)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
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1 Introduction

In the field of solar energy, the provision of clear and brief materials is essential for spreading knowledge and aiding stakeholders in making informed decisions. Fact sheets serve as concise, easily digestible documents that provide essential information about solar energy technologies and their applications. They typically include data on the latest advancements, comparisons between different technologies, and their suitability for specific building needs, climates, or regions. In the context of the SEBs (Solar Energy Buildings) Task 66, fact sheets are designed to complement previous research results like the Technology Radar from Deliverable D2 by offering quick and accessible insights into the current status and potential of various solar technologies. The authors of the individual fact sheets are representing industry and research partners. They summarize key attributes, benefits, and limitations, allowing stakeholders to make informed decisions quickly. The Fact sheets present complex information in a simplified format, making it easier for decision-makers, engineers, and other stakeholders within the SEB business to stay updated on the status and development of solar technologies. By standardizing the presentation of data, fact sheets enable straightforward comparisons between different solar technologies.

The collected fact sheets also help to define solution sets as they are thematically categorized in generation, storage, buildings and communities, and grids. They provide an overview of how different technologies can be integrated to create effective solar energy systems, addressing the unique requirements of different buildings or regions. The information contained in fact sheets contains references to scientific sources and current publications and therefore allows for the identification of areas where more research is needed, particularly in understanding the long-term viability and cost-effectiveness of emerging technologies. The fact that a good component does not necessarily guarantee a good system highlights the need for continued research and demonstration projects, particularly in collaboration with research institutes. Therefore, a specific focus of every fact sheet is also the showcasing of example applications.

While the collected information is effective in summarizing key points, the ultimate decision on adopting a technology should be supported by practical demonstrations and collaborations with research institutions, as paper-based assessments alone may not fully capture the complexities and real-world performance of solar energy systems. This ongoing need for research is crucial for advancing the SEB sector and ensuring that the technologies adopted are not only cutting-edge but also practical and reliable in real-world applications.

Further effort needs to be put on distinguishing cost per kilowatt-hour (€/kWh) of different technologies, which is a critical factor for decision-making in the energy sector. Understanding the cost implications helps businesses and customers evaluate the economic viability of different solar energy solutions. Additionally, the consideration of life cycle assessments (LCA) is needed to ensure that the chosen technologies are sustainable in the long term.

2 Generation technologies

2.1 Evacuated tube air collector

Evacuated tube air collectors are innovative solar systems that capture the solar radiation very efficiently and convert them into usable heat. This technology is ideal for heating air for a variety of applications, such as space heating, water heating and heat for process industries (Sulaiman et al. 2023). A vacuum gap in the tubes creates an excellent thermal insulator, minimizing heat loss and allowing higher temperatures to be achieved (Dubey und Arora 2020). The use of a vacuum tube air collector was intensively investigated as a heat source for a seasonal sorption heat storage system (Weber et. al. 2016)

An evacuated tube air collector system consists of several key components that work together to effectively capture and utilize solar heat. These include:

- Evacuated tubes: Cylindrical glass tubes that have a vacuum space between two layers. This minimizes heat loss and increases thermal insulation.
- Absorber tubes: These are located inside the vacuum tubes and are coated with a highly selective material that effectively absorbs solar radiation and minimizes heat loss. The air flow, which is heated, passes through these tubes.
- Highly reflective mirrors: these mirrors, situated between the vacuum tube and the absorber tube, direct incident solar radiation to the absorber. In this manner, solar energy is captured even under diffuse light. Furthermore, these mirrors are shielded against external contamination."Insulation: placed around the distribution casing at the inlet and outlet of the collector.
- Ventilation system: includes fans or blowers, often driven by photovoltaic panels, to circulate air through the collector and ensure efficient heat exchange.
- Control system: manages the operation of fans and other system components based on temperature settings or specific operating requirements.

The Figure 1 shows the internal configuration of the Airwasol evacuated tube.

Figure 1: Cross-Sectional View of a double-ends open Evacuated-Tube (Source: airwasol GmbH & Co. KG).

Working principal of evacuated tube collector

Evacuated tube air collectors start with cold air being introduced into the distribution box and circulated through the collector by the ventilation system, as shown in Figure 2 (blue arrow, bottom left). Solar radiation passes through the outer glass tubes and is absorbed by the inner absorber tubes. The vacuum between the tubes acts as an effective thermal insulator, drastically reducing heat loss. As the air passes through the absorber tubes, it absorbs the heat, reaching temperatures in excess of 130°C (Agrawal et al. 2023). The heated air is then directed through the collector's insulated header and transported to the consumer, as shown in Figure 2 (red arrow, top right). In addition, this type of collector offers the flexibility to freely choose the position of the inlet and outlet, and its modular design allows for flexible and optimised expansion and connection of the collectors. As the heat transfer medium is air, there is no risk of frost or overheating.

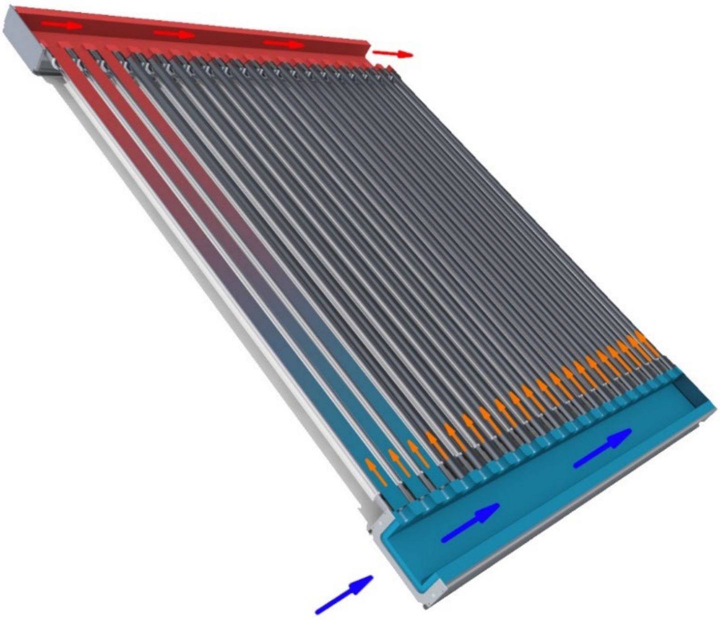


Figure 2: Evacuated Tube Air Collector Unit (Source: airwasol GmbH & Co. KG)

Applications

Vacuum tube air collectors can be used in a wide range of residential, commercial and industrial applications, including heating and domestic hot water as well as direct room air heating. They can also be used for process heat recovery, for example in powder coating, cement production or drying agricultural products.

Summary

Overall, evacuated tube air collectors offer an efficient way to utilize solar energy and support various applications. Their modular design, easy expandability and safe operation make them an attractive option for sustainable heat supply systems. The use of air as a transfer medium ensures simple and fundamentally safe operation, avoiding risks such as leakage, overheating or the formation of steam.

2.1.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

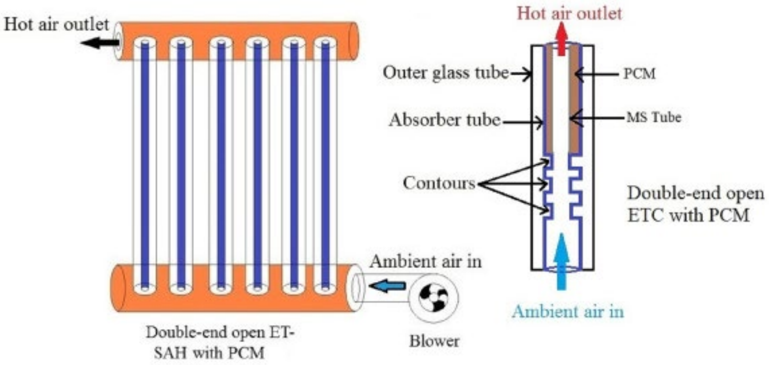
renewable energy generation
heating and or cooling
thermal energy storage

building construction/renovation
energy self-resilience
thermal comfort

2.1.2 Examples

Evacuated tube air collector (airwasol) installed on the roof of the research building at the University of Stuttgart (Source: Institute for Building Energetics, Thermotechnology, and Energy Storage at the University of Stuttgart)

(a) The evacuated-tube air collector: overall view of the experimental set-up; (b) the drying chamber (Chr. Lamnatou et al. 2012).



Double-ends open evacuated tubes with acetamide i.e., phase change material (PCM) for heat storage on the performance of solar air heater (Abhishek Tiwari und Amit Kumar 2023).

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airwasol GmbH & Co. KG. For more information about the company, please visit their homepage at https://airwasol.de

Institute for Building Energetics, Thermotechnology, and Energy Storage at the University of Stuttgart. More information about the project can be found at https://www.igte.uni-stuttgart.de/forschung/aktuelle/SolSpacesE/

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2.2 Brine-air heat pump collector

PVT-collectors combines the high efficiency of ground source heat pumps with the advantages of air source heat pumps. Silent operation and flexible roof or facade installation make the collector an attractive energy source for both electricity and heat.

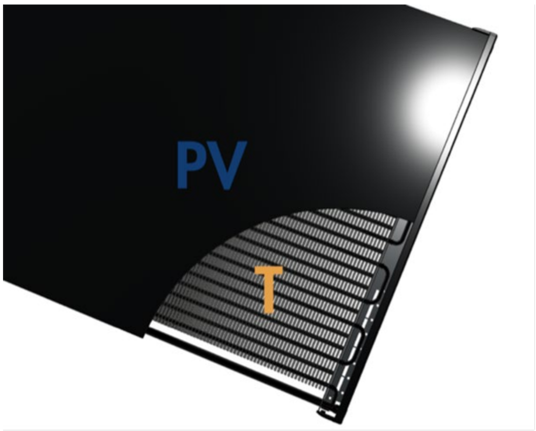

Figure 1: PVT collector.

PVT-collectors, see figure 1, were specially developed for heat pumps. Electricity and heat are generated simultaneously by combining photovoltaics (PV) and solar thermal (T) technology. The heat exchanger on the collector's underside complements the solar thermal heat generation with energy from the surrounding air and provides a reliable heat source to the heat pump even at night.

In this way, PVT-collectors enables the typically high efficiency of brine heat pumps without the need for earthworks or probes, see figure 2. In addition, this brings the advantages of silent operation and flexible installation on roofs or facades. These qualities make the PVT-collector exceptionally attractive as an energy source.

Due to the high efficiency heat exchangers, it is not necessary to couple the collectors with geothermal probes or other in-ground heat sources. This results in climate-friendly heating systems with low operating costs, which generate the equivalent of their own electricity consumption over the course of the year.

DUAL USE OF THE ROOF

The roof surface can normally only be used once for electricity or heat production. With PVT-collector, an approximately 8-fold larger surface area on the reverse side effectively harvests environmental and solar heat from the air and simultaneously makes use of PV module waste heat. In this way, the entire heat requirement of the building can be satisfied directly and the annual average electricity consumption of the system produced. Due to the large heat exchanger surface, this is possible within a significantly smaller roof area compared to other PVT collectors.

SILENT OPERATION

PVT-collector does not require the usual fans or a separate outdoor unit. Compared to an air-source heat pump, the saved installation space can be enjoyed in peace.

WITHOUT GEOTHERMAL PROBES

Until now, probes or ground heat exchangers had to be laid via earthworks to ensure low power consumption. PVT-collector makes this unnecessary. In most cases, roof surfaces are sufficient. If necessary, the façade may also be considered. With similar investment costs, the overall economy is greater.

HIGHER PERFORMANCE BOOST, QUALITY AND DURABILITY

The large air heat exchanger ensures a lower module temperature compared to standard PV panels even when the heat pump is not operating. An approximately 6-10 % higher electrical yield and a reduced maximum module temperature lead to a long service life.

Figure 2. PVT/heat pump system, Illustrative example system (includes third-party components offered separately)

ECONOMICAL SOLUTION

The economical solution offered here is based on several factors that work together to reduce operating costs and ensure an efficient energy supply in the long term.

- Reduced running costs due to highly efficient and energy-saving heat pump operation
- Comparable investment costs to ground-source heat pumps with PV
- Save on electricity costs with self-production

FLEXIBLE RANGE OF APPLICATION

- Single- and multi-family residential
- Office and commercial buildings
- Municipal buildings
- Cold district heating networks
- Swimming pools
- Replacement / supplement to borehole fieldsContribution to Solar Energy Buildings

2.2.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

thermal energy storage

thermal comfort

2.2.2 Examples

Town hall in Offenbach an der Queich

The new town hall in Offenbach an der Queich is supplied with energy via 100 PVT-collectors. The building forms the starting point for a cold local heating network that will supply other buildings in the neighbourhood. In addition to supplying heat to the building, the meeting room is air-conditioned via PVT.

Apartment block in Karlsruhe

The apartment block (built in 1963) in Karlsruhe Durlach was renovated in 2019 to improve its energy efficiency. 100 PVT heat pump collectors with a 55 kW heat pump were installed to heat the 35 residential units (2,300m2 living space) with energy from the sun and air; a gas boiler (90 kW) also provides peak load coverage.

Author:

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2.3 Hybrid Vacuum-Tube PVT

Hybrid Vacuum-Tube Photovoltaic Thermal (PVT) collectors simultaneously generate electricity and heat from sunlight. They are specifically designed to maintain high electrical and thermal efficiency, as well as reliability and longevity, whilst delivering heat at temperatures up to 80C. This operation temperature range means it can be applied directly to space heating, sanitary hot water, swimming pools and low temperature process heat, without the need for a water-water heat pump to upgrade the temperature output. These applications cover over 50% of global heat demand (International Energy Agency 1-3). The low profile of vacuum-tube PVT collectors facilitates mounting on flat roofs, sloped roofs and vertical facades. Some vacuum-tube PVT collectors incorporate integrated reflectors and a mounting geometry that maximises energy generation per m2 of roof used, which is of particular importance for commercial and industrial buildings, which typically have dense energy demand over a small footprint.

Photovoltaic (PV) cells, generally made from silicon, are the basis of the electricity generation. These PV cells only use the part of the solar spectrum with wavelengths below 1.11 μm (Kumar, Rakesh, and Rosen, 2011), resulting in a sunlight-to-electricity conversion efficiency between 20 and 25%. The majority of the remaining 75-80% of the sun’s energy is converted to heat. Additionally, PV cells decline in efficiency with an increase in temperature. This rate of efficiency decline is based on the cell structure and material and is known as the temperature coefficient. A typical temperature coefficient is around -0.39 %/°C for mono-Si PV cells (Baghel, Singh, Chander, 2022).

An evacuated-tube PVT collector generates heat by mounting PV cells onto a heat exchanger, called an absorber, so that the ‘waste’ heat from the PV conversion process can be captured in a working fluid. So-called “water PVT” collectors use a water-based fluid to transfer heat from the collector to the rest of the system via a network of piping. In a PVT collector, the efficiency of the PV cell is added to the efficiency of the thermal capture to calculate the total collector efficiency. When discussing the efficiency of a solar thermal device, it is important to take into consideration the target temperature, ambient temperature, and mean fluid temperature. It is common to see solar thermal collectors with zero-loss efficiencies around 60% (Mellor et al., 2018). The electrical output is captured using standard stringing of the PV cells to a junction-box, which is accessed from the outside using standard PV connectors. Arrays of PVT collectors can be connected to string inverters or microinverters to produce AC electricity in the same way as standard PV panels. In general, the building integration of evacuated tube PVT collectors is identical to that of PV and solar thermal systems. Lastly, racking and mounting systems are designed to deliver the best energy returns to the customer (Duffie, Beckman, 2013).

Solar PVT collectors experience convective losses as their temperatures increase, decreasing the efficiency of the collector as the temperature rises. It is typical to see a temperature delta between the collector and the ambient temperature of up to 100 °C. Flat plate collectors use a considerable amount of insulation to reduce losses, but the absorber side must remain uninsulated. A new, innovative technique for improving PVT efficiency is to encapsulate the PVT inside a vacuum tube. The goal of the vacuum is to eliminate convective heat loss at the absorber. The inclusion of a vacuum is highly effective and can lead to a stabilization of efficiencies across many temperature ranges. In Figure 2 from Mellor et al, the results of a efficiency study shows that an evacuated solar thermal collector can remain at efficiencies above 70% for target temperatures around 60 °C. Evacuated PV cells perform similarly, with efficiency curves flatter than other forms of insulation such as argon or air (Mellor et al., 2018).

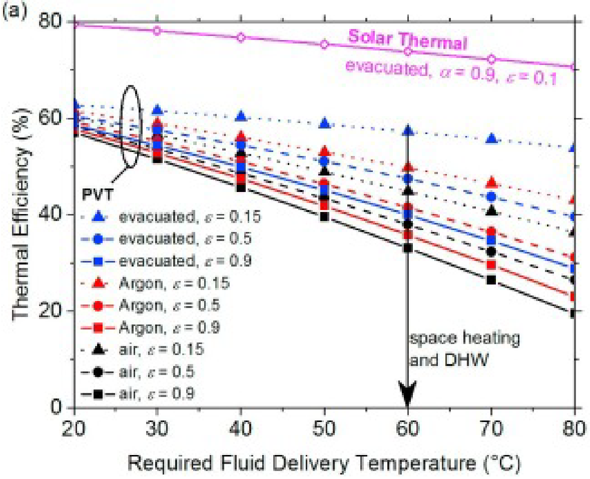


Figure 2. Effect of Insulation types for PVT configurations (Mellor et al.,2018)

The system design for a PVT installation is unique to each end-user, but there are certain components which are required for every system. Indirect systems, in which the solar fluid is hydraulically separated from the potable hot water is preferred in the industry due to safety concerns and longevity benefits. In an indirect system, the primary solar loop transfers heat captured by the PVT to either a heat exchanger, a solar buffer tank, or a combined hot storage tank. A secondary loop transfers the heat from the hot storage tank to the desired use sink. If there is a separate solar buffer tank and hot storage tank, there is an intermediary transfer loop which takes hot water from the top of the solar buffer and transfers it to the bottom of the main storage tank. An auxiliary heat source is generally required for periods of low irradiance. The auxiliary source typically heats the main storage tank directly. Common design constraints include designing for the prevention of legionella, mechanical plant room space constraints, and designing for the required target temperature of the application.

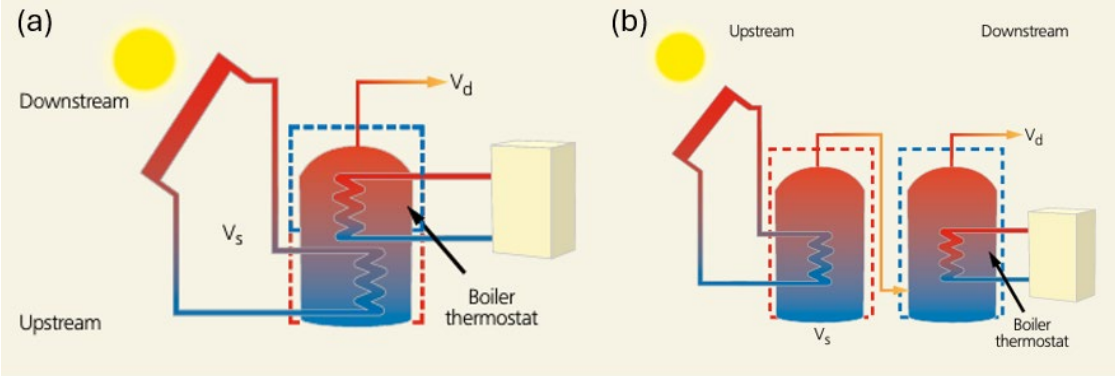


Figure 3. (a) Solar thermal system using a combined solar tank. (b) Solar thermal system using a solar buffer tank and a solar storage tank (Energy Saving Trust, 2019).

PVT systems are financially attractive due to the high total value of energy produced per m2 of roof space (electrcity and heat). It is important to balance customer requirements with what can be achieved given the available solar resource. Solar PVT systems are relatively capital intensive but given the greater output per unit area of roof surface, total lifetime financial returns are higher than conventional PV systems. The PVT system components associated with capital costs are shown below in Table 1. Additionally, there are labour costs for installation and operations and maintenance (O&M). The maintenance associated with a PVT system includes simple visual inspection of the collectors, online monitoring of performance, and replacement of the solar fluid every five years.

Table 1. PVT system components

PVT Specific Components	Piping Components	Sensors and Controls
PVT Collectors and Mounting	Three way control valve	Solar Controller
Solar Buffer Tank	Thermostatic Mixing Valves	Datalogger
Heat Exchanger	Non-return Valves	Flow Sensor
Solar Pump Station	Isolator Valves	Pressure Sensor
Solar Fluid Expansion Kit	Automatic Air Vents	Temperature Sensor
Heat Dissipator	Piping	Irradiance Sensor
Solar micro inverter	Pipe Insulation	

PVT systems integrate with existing heating technologies and newer forms of low-carbon heating solutions. Many PVT systems are retrofit projects which connect to an existing gas water heater. Heat pumps can also benefit from a PVT system integration. For many markets, heat pumps suffer from both a high capital cost and a high energy cost due to expensive electricity. By integrating with a PVT system, much of the operational expense of heat pumps can be offset through preheating or parallel heating of the store through heat generated, and offsetting the electricity consumed through the electricity generated.

2.3.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

Onsite renewable energy generation

energy efficient building construction/renovation

Low temperature heating and/or cooling

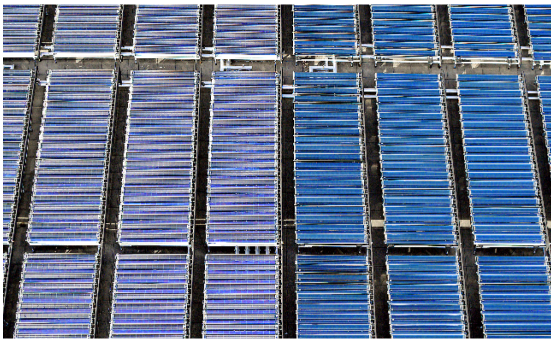
energy self-resilience

Increased thermal comfort

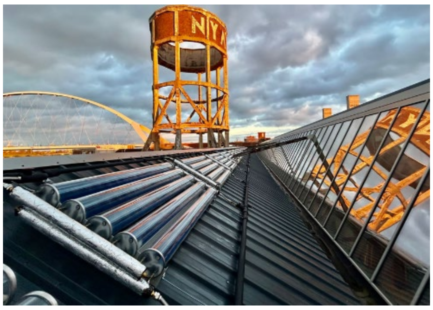
electrical grid stability

2.3.2 Examples


Façade-mounted VirtuPVT collectors from Naked Energy Ltd (Naked Energy. “SPECIFIC IKC – The Active Office.”)


VirtuPVT and VirtuHOT collectors from Naked Energy Ltd on the British Library


VirtuHOT collectors from Naked Energy sharing roof space with PV modules (Naked Energy. “Westgate Leisure Centre.”)



VirtuHOT collectors from Naked Energy (Naked Energy. “Nyma Makersplaats.”)

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2.4 Air Based PVT Solutions

Solar Hybrid PVT Systems General Background

Solar hybrid PVT systems are based on solar receiving modules that when exposed to sunlight has both an electrical generating capability through an arrangement of Photo-voltaic (PV) cells and a further thermal generating capability by the inclusion of a thermal (T) element to the module. This can be seen in figure 1. Further some types of PVT modules have the extended capability of harnessing the cooling effects at night through the night radiation cooling effect.

Solar Hybrid PVT Solutions are an emerging technology platform that demonstrates great potential to reduce emissions, improve energy resilience and improve air quality both within dwellings and externally. Whilst electricity can be delivered over long distances, thermal energy cannot. So, the localisation and efficient use of space (rooves and farm land) is critical in meeting these objectives. So, the ability to harness more of the sun's energy for a given area through PVT solutions will facilitate this.

The versatility of Solar Hybrid PVT systems is demonstrated through their diverse applications. In residential settings, these systems can provide electricity for household appliances while supplementing hot water or space heating needs. Similarly, in commercial buildings, PVT solutions can contribute to powering ventilation systems and providing heating, ventilation, and air conditioning (HVAC) services. Industries can also benefit from the integration of PVT systems into their processes, optimizing energy usage and reducing operational costs.

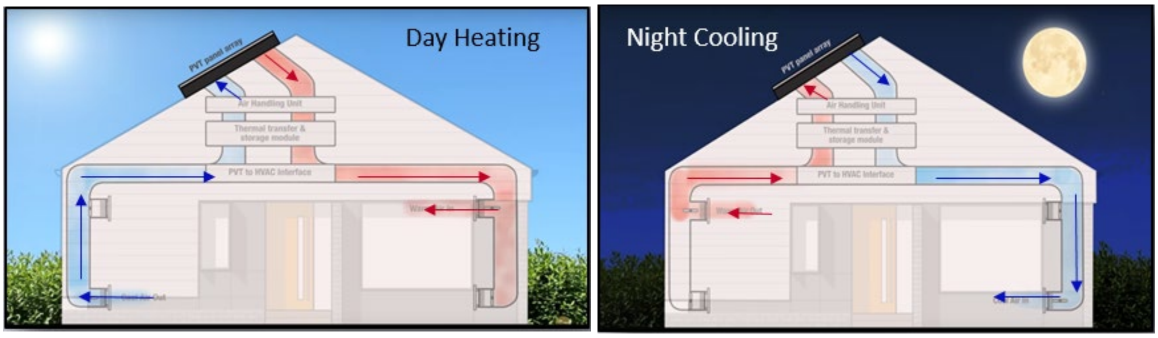


Figure 1: Application of Air Based PVT Solutions in a Domestic Setting (Image Credit: Sunovate)

Solar Hybrid PVT Module Taxonomy

The now completed IEA SHC Task 60 – PVT collectors (https://task60.iea-shc.org/about) prepared a one page "Design Guidelines for PVT Collectors" factsheet (https://task60.iea-shc.org/Data/Sites/1/publications/IEA-SHC-Task60-B2-Design-Guidelines-for-PVT-Collectors.pdf). The fact sheet illustrates and explains a comprehensive list of all the possible topology variations of PVT modules that are in the market or have been researched. With reference to this it makes it easier to compare the different modules using liquid or gas as the primary heat transfer medium. In some cases when a refrigerant is used directly in the modules a combination of the liquid and gas phase however nearly all applications of this approach more closely resemble the liquid module construction. The most common gaseous working fluid is air, although other specialty gasses could be applied in custom applications for increased heat transfer or flame extinguishing properties.

Solar Hybrid PVT Modules Topology Types

There are 4 main PVT module types, which can be seen in figure 2. The most common type is the Wind Irradiance Sensitive Collectors (WISC) [or sometimes referred to as the Uncovered module]. This looks very similar to the standard PV module. It's called a WISC modules as the exposed upper surface is very susceptible to wind and convective driven thermal losses. This can reduce thermal capture performance considerably. The next type is a Covered module. This is much like the WISC except it has an additional glazed layer which introduces and insulating air gap (at atmospheric pressure) between the outer glazing and the inner PV cell encapsulated glass pane below it. The air gap and glazing considerably reduces the effect of wind and convective losses during the daytime. However, the additional insulation and glazing does have an impact night radiation cooling performance. The third module type is an Evacuated Tube type. These solutions breakaway from the more traditional PV module format. They tend to house a single string of PV cells inside an evacuated tube with the surrounding gaseous pressure well below ambient conditions. The combination of glazing and very low pressure within the tube further reduces thermal losses and usually results in higher attainable outlet fluid temperatures than the Covered type. A market example of this is Naked Energy’s line of products. The fourth module type introduces a degree of solar amplification or concentration via a reflective or diffractive process. The basic PV cells are the same but the focused light means that the heat being generated needs to be removed to ensure safe PV cell temperatures at all times. These PV cells can also be housed in an evacuated tube like Naked Energies VirtuPVT solution (https://nakedenergy.com/products) or semi enclosed housing like the Solarus C-PVT product.

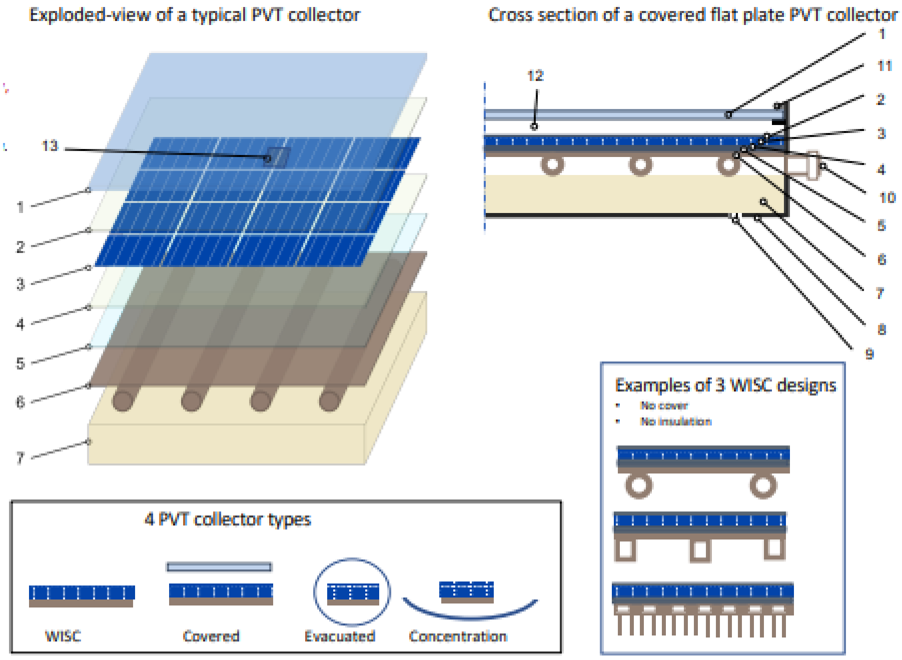


Figure 2: Design Guidelines for PVT Collectors. (Extract from IEA SHC Task 60)

Solar Hybrid PVT System Selection

The selection of what type of Solar Hybrid PVT solution and preferred working fluid (liquid, air or refrigerant) is entirely dependent on the type of application and associated infrastructure the hybrid PVT system will be interacting with. In the simplest form air-based PVT solutions can service space heating and cooling directly and liquid water-based PVT systems can service hot water heating directly. Both only require a simple control system and a working fluid movement device like a fan or pump respectively. From this most basic system they can become infinitely more complex in interactions with other equipment such as storage, boosters heat pumps and appliances. Complexity also comes in the form of managing extreme environmental conditions (freezing or high temperatures) and off design operations (thermal over production – energy dumps or loss of working fluid leaks) to prevent system damage.

In more complex and multi service application the selection process typically requires a detailed energy audit and load model to be developed. This together with a local climate model enables various system sizes and configurations to be evaluated to provide the optimal solution for the application.

Irrespective of system complexity and working fluid, the understanding of local climatic conditions and module type performance are critical to a successful design. These parameters dictate not only yield but also maximum PV cell stagnation temperatures (no fluid flow equilibrium conditions). In some cases, the stagnation temperature may never exceed an internal room temperature or a domestic hot water specification set point. In response to such a situation a designer may elect to change from a WISP module type to a Covered PVT module or Evacuated tube. Alternatively, the designer may introduce and external supplementary booster source such as a heat pump or electric resistance thermal toping cycle. In this case the PVT system undertakes a pre-heating function.

Solar Air Heating Market

Solar Air Collectors (SAC) (thermal only) or Solar Air PVT’s have often been overlooked in modern literature as a pathway towards decarbonising heating and cooling sectors. Some of this can be accounted by the success of solar hot water heating sector and its respective associations maintaining the supportive government policy focus. The solar air heating sector didn’t receive the same amount of support so didn’t scale to the same extent. Some of the attitudes towards solar air Hybrid PVT Solutions have carried on from the historical assumptions around SAC’s.

The recent Solar Heat Worldwide 2023 – Global Market Development publication indicates that there is a cumulative 774 Mm^2 of solar thermal products globally in service. SAC's and PVT systems make up 1.44 Mm^2 and 1.5 Mm^2 of that total respectively. SAC's classification represents both glazed and unglazed segments. The report also provides annual installed capacity metrics. The global market added some 19 GW_{Th} of added capacity in 2022. SAC's added a further 38 MW_{Th} [54,193 m^2] (in 2021) and hybrid PVT systems 42 MW_{Th} (21 MW_e) [82,349 m^2] (in 2022). For the Hybrid PVT market this was down considerably from the previous year annual installations results of 79.8 MW_{Th} (27.6 MW_e) [167,165 m^2] (in 2021). An explanation of this considerable reduction was due to sales in air-based PVT systems which dramatically collapsed from 45.5 % of globally installed collector area in 2021 to 0.0 % in 2022. This was primarily due to the French incentives and grants schemes being withdrawn.

The French market has been a historical anomaly for the air-based PVT segment and a standout globally. Frances strict planning rules required many new PV installations to be built into the roofs (BIPV). This afforded the PV industry together with additional water proofing requirements, the mechanism to draw off the heat from the back of the panels and consume this on premises as space heating with very little additional cost. Whilst these systems are basic, together with the additional grant funding they proved to be extremely popular and with 547,575 m^2 of cumulatively installed area and despite the recent collapse it still remains a significant portion (99 %) of the installed global air module PVT market share and 36 % of the combined air and water PVT market. (Source: Solar Heat Worldwide 2023).

Air as a Working Fluid – Advantages and Disadvantages

Air as a working fluid has many advantages over liquid and refrigerants. It also has some disadvantages in some applications and in constrained installations. Its key advantage of air is that is free and freely available. Excess heat can be discharged to atmosphere at no cost and with just the simple intervention of a dump valve. Liquid systems typically require an additional complex and expensive external cooling circuit. Air can be used directly in applications such as space heating and cooling, process drying and thermal storage solutions such as pebble bed and ground air heat exchangers. Air can exchange its energy to the liquid state across traditional and widely available fin coiled heat exchangers. Air, if it leaks is harmless to occupants, building structures and the environment. Air doesn't freeze or boil across the normal PVT operating range which reduces design complexity or the need to introduce toxic anti-freeze product.

The disadvantage of air is its thermal properties. Air is a good insulator and poor conductor of heat. As a result it likes to generate insulating boundary layers against heated surfaces. These boundary layers when developed reduce the effectiveness of the heat transfer process and resulting module performance. Introducing turbulence breaks down the boundary layer and increases heat transfer. However turbulence also introduces mixing which can be problematic in attaining a higher grade of heat. This is explained further in the module design variation section. Air has a low specific heat capacity of 1.004 kJ/kgK which is a quarter of that for water 4.2 kJ/kgK. So it requires 4 times the mass of air or 3300 times the volume of air to convey a similar value of heat that is equivalent to the capacity of one litre of water with and equivalent temperature lift. The use of ducts vs piping presents some additional physical challenges in transferring the heat from the modules to the consumer. Some of the issues relate to the aggregation of the heat from multiple modules, through to accessing the building through roof penetrations and associated roof and vertical service ducts. Larger ducts also result in larger areas that are exposed to heat losses which either reduces system efficiencies or add more costs.

Special PVT Applications

Solar Hybrid PVT Modules have traditionally been associated with the core application of generating heat during the daytime. There are a number of other applications that extend outside of this that provide greater utility to the system. These include *Night Radiative Cooling, Condensate Harvesting, PV Boost* and *Snow Melt*.

Night Radiative Cooling

Solar PV modules are all influenced by night sky radiation effects to varying degrees according to their topology. The night radiation effectiveness is sensitive atmospheric conditions. Clouds or high suspended particles can block the window to space which is essential form maximum effect. The black colour of the PV cell has a very high emissivity. The WISC topology is most sensitive to this effect as the PV cell is in direct contact with the PV glass allowing the coolth to be to the PV's glass face. The advantage of the PVT system is that it can enhance the effect by shielding out any underside ground or structure reradiating effects which can raise the PV cells temperatures. The PVT module underside provides this shielding through the application of enclosures and insulation. Experimental studies have shown that on a clear still night, with low humidity the PV cell temperature has been measured to be 8 K less than ambient. With the introduction of filtered outside air into the PVT system the air applied to the PV cell then sub cools the air further. A typical PVT system would generate a 3-4 K temperature drop in supply air in his application. In closed loop applications where the air is introduced at higher temperatures than ambient the drop in temperature and the cooling effects are relatively higher. The radiative effects are increased with increasing PV cell temperature as is the additional convective effects resulting from being higher than ambient conditions. Air based PVT systems enable this cool air to be used directly in space cooling. This is an advantage over other systems.

Condensate Harvesting

A subset opportunity of the *Night Radiative Cooling* application is with the right conditions the cooling can precipitate condensation on the panel externally which can be harvested in the same way as rain is. It has been observed the module inclination angle has an influence on the condensate yield. Other applications of condensate harvesting can be performed underneath the module through the introduction humid air into the PVT flow path. The condensation precipitated on the underside can be further harvested with special consideration for collection galleries to be included in the design. This mechanism can also prevent unwanted condensation from entering into the building fabric in areas of high evening humidity when using BIPV methods. The underside condensate harvesting is unique to air-based PVT systems.

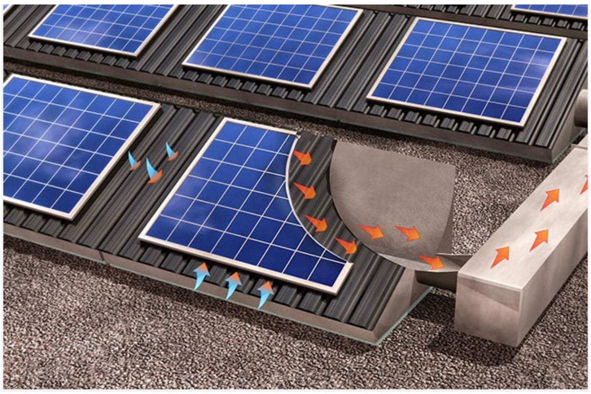
PV Boost

PV Boost is an electrical output enhancing feature. The idea behind this it to be able to actively boost the PV output at times of high electricity market demand. Air pre-cooling enables the system to bring down the PV cell temperature well below the point it can do with just ambient air. This inlet cooling can be achieved with evaporative means, exchanged with chilled thermal storage or ground heat exchangers. In some environmental conditions such as a very hot dry still day, an inlet cooled system could boost an additional 20 % gross output. It is important to acknowledge that for the greatest effect even *PV cell cooling* and *PV cell venting* is required.

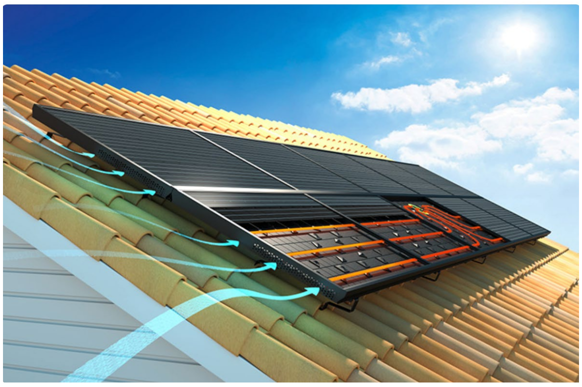
Snow Melt

It has been recognised that in higher elevation and latitudes that significant winter electrical and thermal production can be lost which can be attributed to snow coverage. Melting the snow off to accelerate access to a clear whole panel is desirable to reboot production and as a safety measure to reduce the need to remove manually or have significant chunks falling from heights. The air-based PVT systems are well suited to this application as only a small amount of thermal energy is required to break through the snow on and initial bank of cells. The additional thermal energy generated from the cleared cells can then be used to drive the final thermal demand to clear the remainder of the snow from the modules in the array.

2.4.1 Examples



Solar Wall: This is a commercially available solution. It uses transpired black metal sheeting which acts as the absorber. As the air is drawn through and towards the back of the module it sucks down on any heated air established behind the module and any reradiated thermally generated boundary layer on the metal perforated sheet. (Image Credit: Solar Wall)

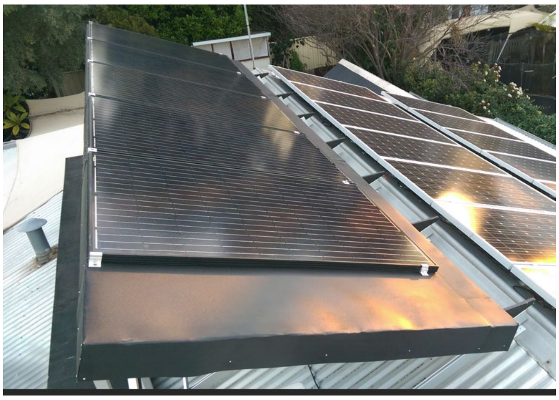


Systovi – R-Volt: The R-Volt solution is one of the simplest forms of an air-PVT solutions. It comprises of an integrated moulded waterproofing membrane sheet which is configured in the fixed open loop primary air handling variation with a Multi-Modules flow path transverse. The secondary air handling flow is characterised by vents through the side of the PV frame to enable the air to flow to the underside of the module before traversing across several modules typically to single common outlet. The Integrated moulded membrane sheet has a number of upward impressions (bumps) included to provide some minor turbulence enhancing features. (Image Credit: Systovi)

GSE Intergration – Aerovoltaic System: The In-roof solution provides a water proofing membrane frame and a PV module mounting fixture (and other components like micro inverters if used). Each frame has at least one cut out to service electrical cables. These cut outs can also serve as mounting bracket to fix an outlet ducting transition piece to. This transition piece can then interface with any stand air ducting. In GSE's case the ducting solution can then interface with their Air'System which has fans, filtration and flow control features included within. In these cases the air is then drawn in from the underside edge of the PV modules frame and then reports to its own discrete outlet port. (Image Credit: GSE Integration)

Meyer Burger – Solar Tile: The solar tile is an encapsulated product that sits in a much smaller dimensional format to the traditional PVT solutions. The tiles are aligned with each other on the inclined slope. This enables the higher modules inlet to sit immediately above the lower modules outlet. The air can naturally ventilate or be induced by a fan. The module has an upper and lower section to encapsulate the air within the flow path. The module appears not to have any additional enhancing features associated with increasing the heat transfer within the flow path. However even though it would be considered an *Open Path* module the short effective flow length due to the much smaller tile size and the need for the air to change direction as it passes through each module, it could be considered that this design would have a similar HTE outcome to that of a larger format module with *Single Serpentine Path* flow. (Image Credit: Meyer Burger)

BASE-Innovation - Cogen'Air: The Cogen'Air module has both an air tight enclosure glued to the rear of the PV module to contain the working fluid and it also has aluminium plates and fins glued to the back of the PV module. This enhances conduction of heat into the air stream by providing a number of hurdles to which turn the air over as it progresses from inlet to outlet. The enclosure has 3 inlets and outlets together with two mid panel dividers axial to the air flow direction, to create 3 separate flow paths. This air distribution aims to reduce the potential for flow stagnation. The extension of the aluminium conductors also aim to conduct the heat from the enclosure sealing lip back into the vented area so as to reduce the heat building up under the fixing flange. (Image Credit: BASE-Innovation)



Sunovate: The Sunovate PVT module is unique in that it's the only module design known that can apply inlet air and also vent the spent heated air at a PV cell or sub-PV cell scale. The Sunovate system was primarily designed to enhance the PV electrical boosted performance and module life. It achieves this by keeping the cells evenly cooled and by keeping peak PV cell temperatures much lower over the module's lifetime respectively. To deliver this outcome the module requires a high level of precision in how the air is delivered and drained to ensure a balanced air flow across the PV cells. Further this precision is needed to be sustained across a range of flow rates. The design results in a very high HTE across a range of flow rate conditions which extends its operational range from day time thermal capture to night radiative cooling with minimal fan power. (Image Credit: Sunovate)

2.4.2 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation	building construction/renovation
heating and or cooling	energy self-resilience
thermal comfort	electrical grid stability

2.4.3 References

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2.5 Open sorption system for comfort cooling using solar-air dehumidifier

The components of a solar driven open sorption system for comfort cooling of buildings are an air solar collector with a desiccant layer (a so-called solar dehumidifier), a cold storage with desiccant, fans powered by PV panels, an electric battery, a ventilation duct system with valves and a control system.

Figure 1 shows the design and operation conditions of the solar dehumidifier. During the day, when the sun is shining the desiccant layer consisting of silica gel is dried out and then used to dehumidify the ventilation air during the night when air flows through the dry silica gel. At night, the ventilator is powered by electricity from the grid or a battery.

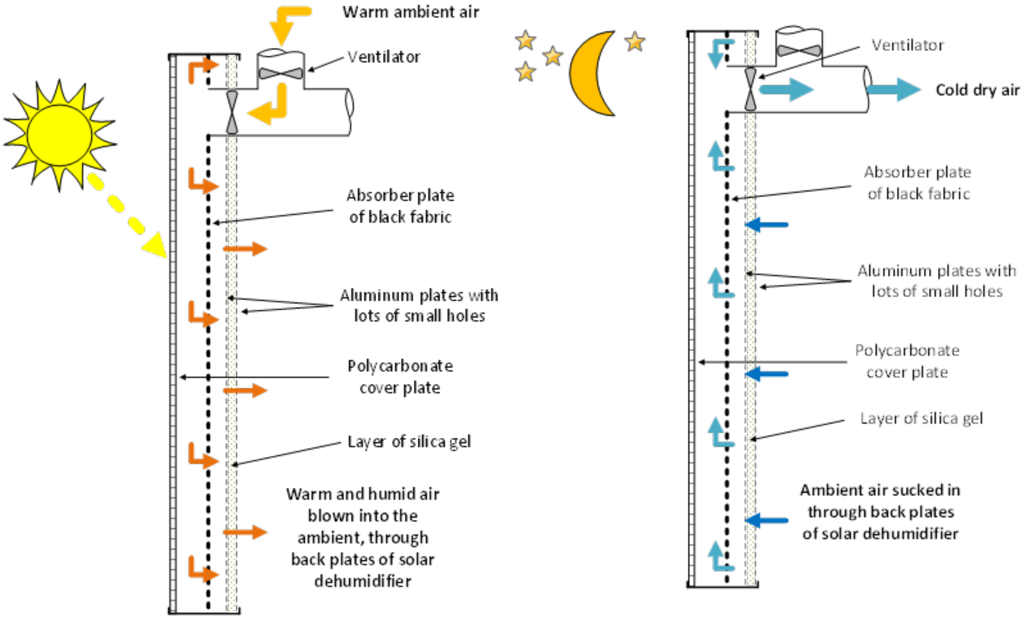

Figure 1: Principal drawing of the solar dehumidifier in charging mode (left) and discharging mode (right), Andersen and Furbo, 2017.

The two main components of the open sorption cooling system, the cold storage and the solar dehumidifier, both use a non-hazardous adsorption material and water vapor of an air stream as a working pair. Research by (Neyer and Mugnier, 2018, Mugnier et al., 2017, Vasta et al., 2018, Grzebielec and Szelagowski, 2018, Rouhani, 2019) has demonstrated that different storage types and principles can be used to store cold. Open adsorption systems with silica gel offer inexpensive and simple cold storage. Such systems combined with solar air collectors allow for solely solar-driven operation (Nielsen et al., 2019). The principle of the cooling system can be described as an open adsorption heat pump in intermittent operation, see Figure 2.

The solar air dehumidifier works as the thermal compressor, and the storage works as an alternating evaporator and condenser. The operation sequences work as follows:

A) During sunshine, ambient air is lead through the solar air dehumidifier, where it is heated before passing the implemented desiccant layer. With a flow rate of about 70 m³/h per m² collector, air temperatures of typically, 50-60 °C are achieved, which allows the release of bound water (Andersen, 2011). The water vapor is released to the ambient. In this way, the solar air dehumidifier is dried.

B) During the nighttime, cool and humid air from ambient enters the solar air dehumidifier where the air is dried due to the implemented layer of desiccant. The dried, cool air stream is lead through the desiccant storage, where previously condensed water (C) evaporates into the air stream. As a consequence, the desiccant storage cools down. The driving force of this process is the partial water vapor pressure difference between the air volumes in the storage (high) and the inlet air stream (low). After several hours of operation, the storage dries and cools close to ambient (night) temperatures.

C) When cooling is needed, warm, humid ambient air (daytime) is ventilated through the cold desiccant storage, resulting in cooled and dried air for room ventilation.

In less sunny periods, the energy source for drying the desiccant in the solar dehumidifier can be energy from a PV powered battery or electricity from wind turbines. In this case, the solar dehumidifier must have a built-in electrical heating surface.

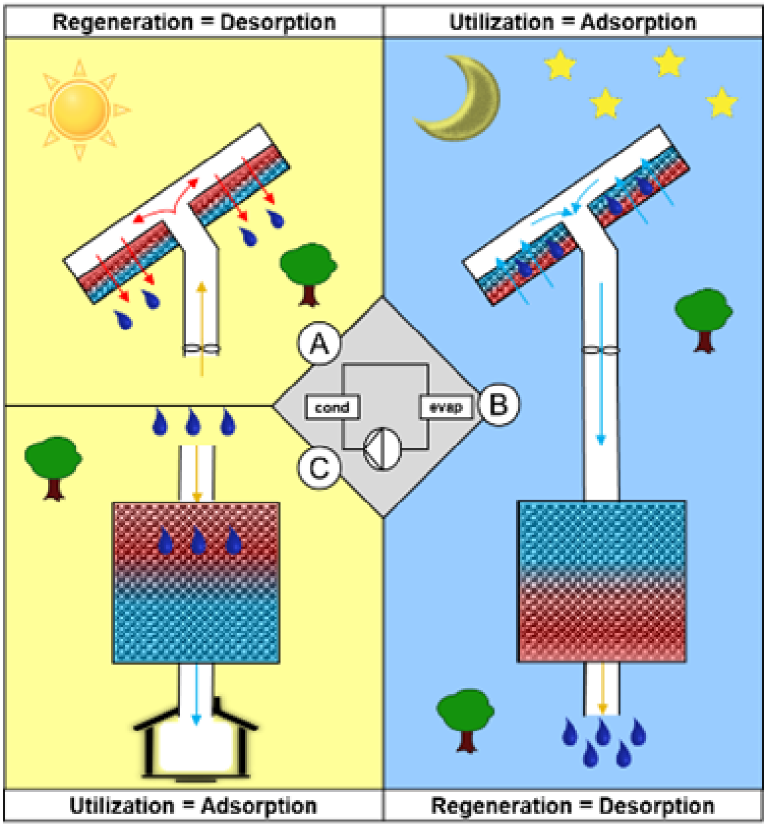

Figure 2: Principle diagram of cooling system, Nielsen, E., Becker-Hardt, S., Englmair, S., Kong, W., Furbo, S., 2022.

2.5.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

thermal energy storage

thermal comfort

building construction/renovation

energy self-resilience

electrical energy storage

2.5.2 Examples

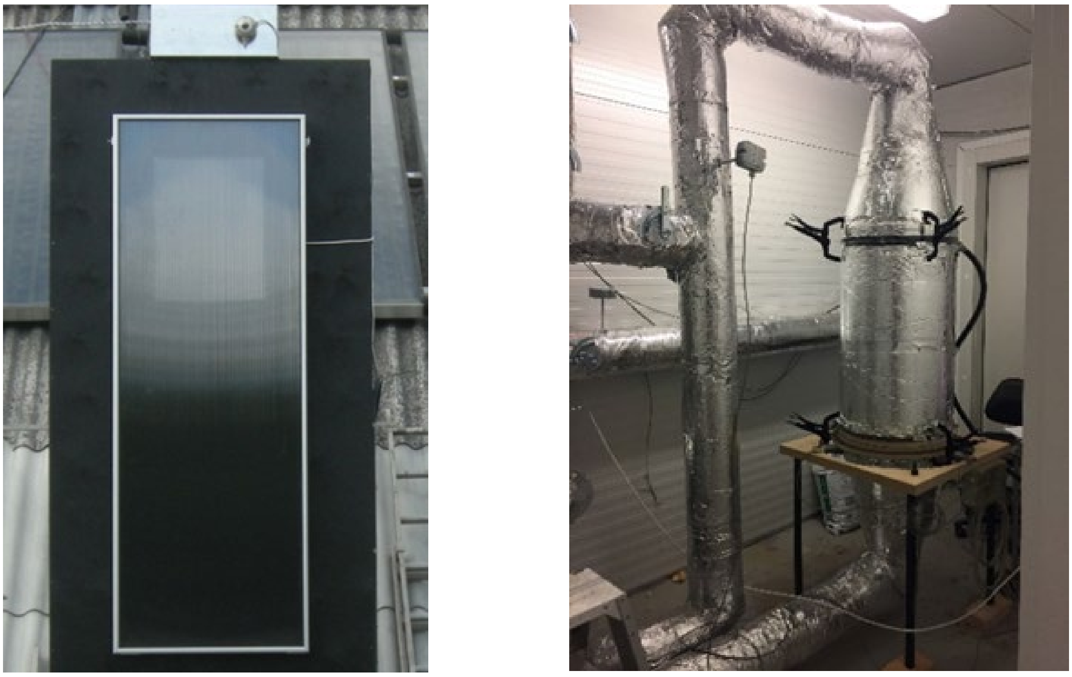

Figure 3 Example: Air solar dehumidifier (Solarventi, Andersen, 2011) (left) Cold storage and ventilation duct system (Nielsen, E., Becker-Hardt, S., Englmair, S., Kong, W., Furbo, S., 2022) (right)

2.5.3 References

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3 Storage technologies

3.1 Rock Bed Storage

Storing thermal energy in rock or pebble beds has been recognized as a cost-effective, durable technology for over a century. Recently, there has been a revival of interest, particularly in the context of transitioning away from fossil fuels. The interest is driven by the need to store thermal energy at high temperatures, especially for solar thermal power plants, process heat or power to heat (PtH) applications.

Rock bed storages rely on a heat transfer medium to allow charging and discharging. Air is a popular choice for its cost-effectiveness, safety, and environmental friendliness. In process heat applications, thermal oils are sometimes employed as the heat transfer medium, albeit with operational temperature limitations around 300°C.

The type of rock is uncritical for low temperature applications like space heating. Some rock types like Dolerite or sandstone are suited also for high temperatures. At very high temperatures exceeding 1000°C, also alternative materials such as ceramic blocks are utilized due to their superior heat durability.

The large surface area within a rock bed enables exceptionally high rates of heat transfer, with over 90% of the medium's energy effectively exchanged with the storage with each volume passing through.

As a result, the fluid exiting the storage retains nearly the same temperature as the final section of the rock bed (see figure 1). This ensures an optimal performance of connected solar thermal air heaters, which provide higher efficiencies at lower temperatures. During the charging process, the temperature gradient progresses gradually from the inlet to the outlet until reaching the end section of the storage, marking the completion of the charging cycle.

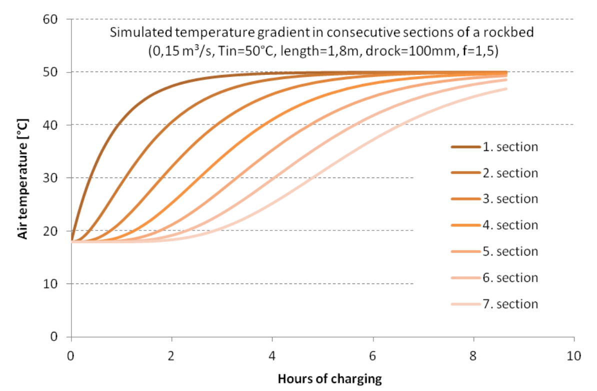

Figure 1: Simulation of temperature gradient in a rock bed during charging with 50°C warm air [1]

Figure 2 illustrates the basic principles of an air-based solar heating systems with a rock bed storage: a fan, potentially powered by photovoltaic module, circulates warm air in a closed loop through the rock bed. The fan operates automatically during sunny periods, reducing speed during cloudy intervals, and switching off at night without need for any control electronics.

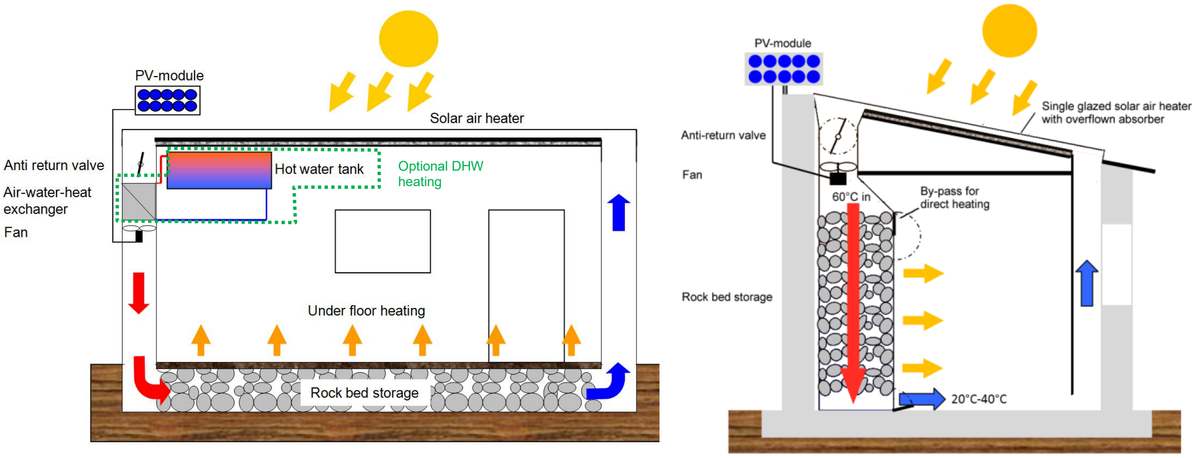

Figure 2: Solar space heating with rock bed applied in projects in the Altiplano and in Ladakh 1997-2018 [1] [2]

In an optimal setup, the rock bed can be situated beneath the room floor, using the "thermal losses" in a controlled way to provide efficient underfloor heating through the thin slab which covers the storage. In cases where it is not possible to place the storage beneath the room (as for example on the second floor) the rock bed can be placed vertically on the wall (see figure 2). Further rooms can be heated indirectly by connecting them to the storage with help of air ducts. During heating, warm air from the storage can be circulated by forced or natural convection to these rooms.

Both systems have in common, that they have to prevent discharge by natural convection during night time, as the storage is situated below the solar air heater. That can be accomplished by a return valve, which automatically opens with the downward air flow and closes when the fan stops operation.

Figure 3 shows the measured temperatures of a living room heated with a solar air based system with rock bed in Ladakh during 4 winter days. Ambient temperatures are going down to -10°C almost each night, with daytime temperatures around 5 to 8°C. The solar air heater heats air up to 70°C during mid day and charges the rock bed storage to 26-30°C in the afternoon. The rock bed serves as underfloor heating and looses 8-10 K overnight. Starting with a fairly discharged storage on the first day, the temperature in the room is kept between 17 to 19° C over the following days, even during days with less solar radiation. Compared to an unheated room in the same house, this shows an improvement of more than 15 K. Experience has shown, that the massive storage is able to provide enough energy for space heating for up to 3 days without sun.

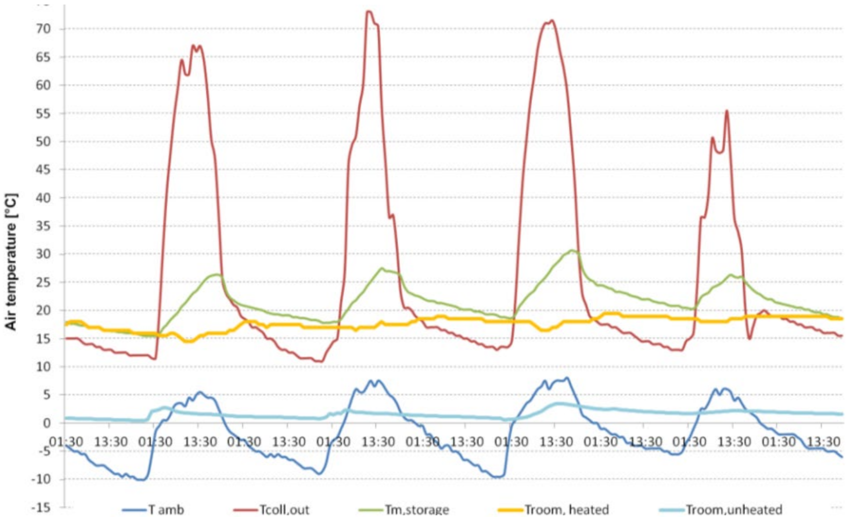

Figure 3: measured temperatures at Kurja Guesthouse in Leh/Ladakh [7]

For low-temperature applications such as space heating, air systems offer significant advantages over water based systems: reliability due to their resistance to corrosion, freezing, and overheating, as well as avoiding dripping losses and the need of anti freezing agent. However, air's relatively low thermal capacity requires a high volume flow to transport energy. Accordingly, careful design of the air duct system and rock bed is essential to mitigate unnecessary pressure drops and minimize the fan power demand. So it is important not to use too small rocks to avoid high pressure drop on one side and not to use too big rocks which reduce the heat transfer rate due to smaller surface area/mass ratio.

Following table summarizes the advantages and disadvantages of water and air based heating systems:

	Water based system	Air based system
Heat transfer media capacity	High heat capacity -> only a small volume flow (0,03 m³/m²h) is necessary, reducing duct size and insulation effort.	Low heat capacity -> high volume rates (air: 40 m³/m²h) and significantly **larger channel sections** are required to cope with pressure drop.
Freezing temperatures	**Danger of freezing**, yearly control of anti freezing agent, as system can get damaged otherwise.	No freezing problems, no anti freezing agent.
Stagnation of solar collector	**High vapor pressure** or high degree of evaporation at stagnation temperature, especially in summer.	No problems of overheating in summer.
Complexity/costs	Corrosion resistant materials like copper, aluminum, stainless steel have to be used, which **increase costs**. Evacuated tubes offer a more economic solution, but have a problem with stagnation in summer. Replacements parts might not be easily available .	Simpler and less expensive, locally available materials can be used. Work effort for the ducts and rock bed storage might be higher, but create more local jobs and value.
Repairs	Repair of the water circuit needs **special know how and tools**.	Reparation of glasses, ducts etc can often be done by the owner.
Circulation	**AC powered** water pumps with thermostats- dependent on unstable grid or AC inverters for PV supply.	DC-powered fans with direct PV supply-> independent/ off-grid, robust.
Leakages	**Sensitive for leakages** in the water circuit- when water is missing in the circuit, operation is impossible.	Leakages are uncritical: no damage , no environmental or health hazard risk from spilled heat transfer medium.
Efficiency	The efficiency at higher temperatures is better than the one of simple air based systems. This allows 20-30% reduced collector area.	Efficiency is competitive at lower temperatures. At higher temperatures the **collector area must be 20-30% bigger** than that of a solar water system to achieve the same energy yield.
Storage	Hot water storage tanks offer a heat capacity of 35 kWh/m³ (dT=30K). Tanks must be made of corrosion resistant materials with sacrificial anode, which must be controlled regularly. The anti freezing/water mixture in the solar circuit must be separated from storage by a heat exchanger.	A rock bed occupies about **four times more volume** than a hot water storage with equal energy content at the same dT. It's construction can be at very low cost, using local materials and labour.
Heat distribution to the room	Separate water based under floor heating with **piping and pump** for circulation is necessary.	Heat is transmitted to the room trough conduction and natural convection as the storage cover is the room floor.
Warm water	Can be provided from the water storage tank.	Warm water can be provided by placing a heat exchanger in the air flow. The warm water system can run without pump and anti-freezing agent.

3.1.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

Onsite renewable energy generation

Low temperature heating and/or cooling

Efficient thermal energy storage

energy efficient building construction/renovation

energy self-resilience

Increased thermal comfort

3.1.2 Examples

Solar air heater at Kurja guest house in Leh/Ladakh [6]

Rock bed during filling at Kurja guest house [6]

Solar air heaters and rock bed before filling at primary school in Misa Rumi/Altiplano/Argentina [2]

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3.2 Latent storage (Ice store)

An ice store uses water as storage medium and can store thermal energy over a long period of time and is therefore used as a seasonal thermal energy store. It is made up of a concrete or plastic tank filled with water and typically two heat exchangers operated with a mixture of water and antifreeze. Like in other water filled tank stores thermal energy can be stored and extracted through changing the water temperature. Additionally, the latent energy of the phase change between liquid water and ice is used in an ice store by freezing and melting the water.

On the left side of figure 1 a cylindric ice store is schematically shown together with the heat exchanger pipes which are installed spiral-shaped on a metal construction inside the ice store. The pipes of the extraction heat exchanger (1) coloured in blue are distributed in regular distances over the height and radius of the cylindrical water body. This extraction heat exchanger is used to extract thermal energy from the ice store through the circulation of a colder mixture of water and antifreeze compared to the ice store temperature. Therefore, an ice layer forms around the pipes when the surrounding water reaches its freezing point. While this freezing process the temperature of the ice store remains constant, as the extracted thermal energy results from the phase change of water. In this case the ice store can be used as a thermal energy source.

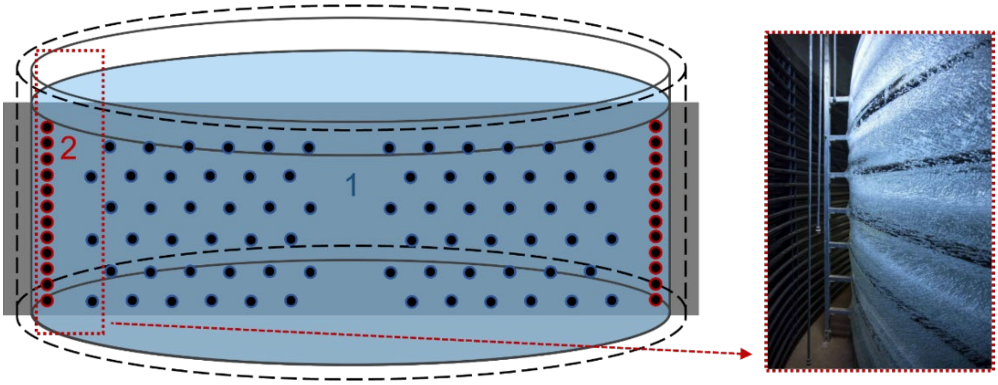


Figure 4: Schematic figure of a cylindric ice store with the pipes of the extraction heat exchanger (1) and regeneration heat exchanger (2) on the left and a picture from inside the ice storage. (Source: IGTE (left) and Viessmann Climate Solutions SE (right))

The pipes of the regeneration heat exchanger (2) coloured in red are located along the side walls of the storage tank. This regeneration heat exchanger is used to store thermal energy in the ice store through the circulation of a warmer mixture of water and antifreeze compared to the ice store temperature.

On the right side of figure 1 a picture from inside the ice storage is shown. As it is marked with the red dotted frame inside the schematic figure of the ice store the picture is taken in the gap between the side wall with the regeneration heat exchanger on the left and the extraction heat exchanger on the right. In this case, the picture shows an ice store that has already been heavily discharged and thus a high fraction of ice exists.

Typically, ice stores are buried under the earth’s surface. As in some months mostly in winter the temperature of the surrounding earth is higher compared to the water temperature inside the ice store there are heat gains from the environment. If the ice store is used for heating purposes this is an advantage compared to other seasonal thermal energy stores with higher temperatures and therefore heat losses.

For the regeneration of ice stores a thermal energy source is needed. Often ice stores are combined with solar thermal air-brine-collectors which can provide thermal energy for the regeneration of the ice store on the one hand. On the other hand, those collectors can be used directly as thermal energy source parallel to the ice store.

Another option for regenerating the ice store is the operation mode “natural cooling”. In this operation mode thermal energy is extracted from buildings for cooling in summer and stored in the ice store.

As a result of the relatively low source temperature provided by the ice store in comparison to other thermal energy stores heat pumps are necessary to increase the temperature to a level that can be used for space heating or domestic hot water preparation. If a central ice store is used to heat and / or cool different buildings a cold district heating network with decentralised heat pumps in the individual buildings is required.

3.2.1 Contribution to Solar Energy Buildings

- Primary contribution
- Secondary contribution

Heating and / or cooling

Thermal energy store

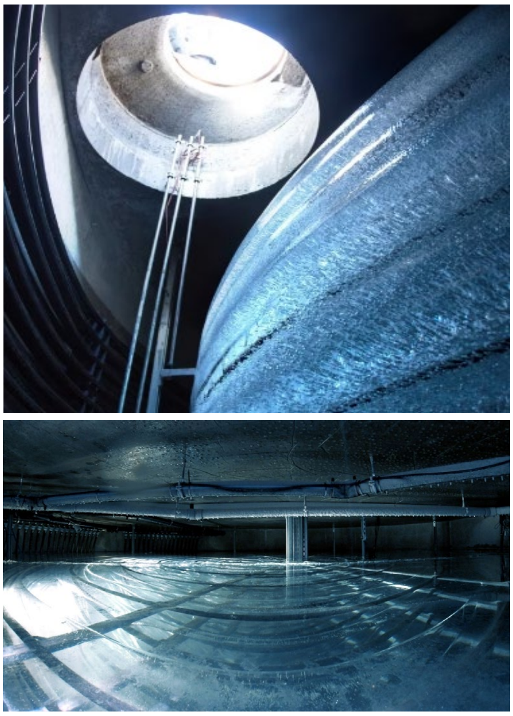
Increasing the degree of utilization of renewable energy generation

Thermal grid capacity

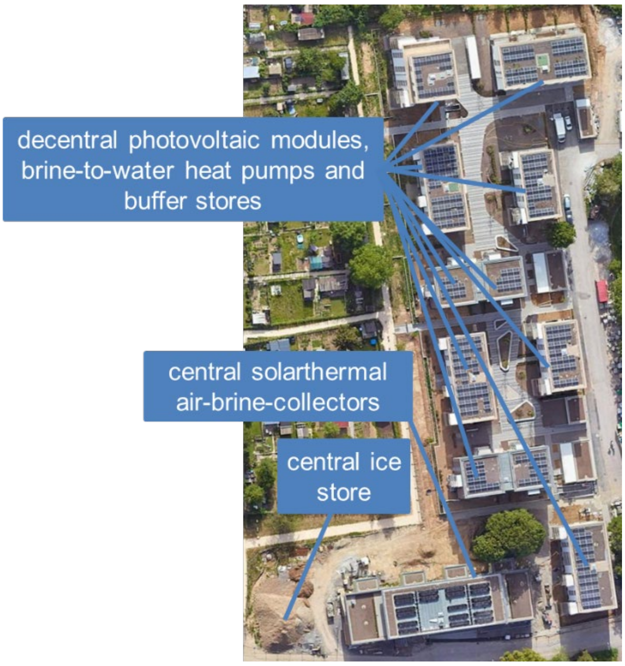
Thermal comfort

Electrical grid stability

3.2.2 Examples



Interior views of an ice storage tank filled with water or ice. With the extraction heat exchanger inside (on the right in the upper picture) and the regeneration heat exchanger outside (on the left in the upper picture) (Source: Official marketing image from Viessmann Climate Solutions SE)



Aerial view of demo case no. 22 Ludwigsburg of IEA SHC Task 66 with central ice storage and air-brine collectors, cold district heating network, and decentralized heat pumps for heating and cooling in individual buildings. (Source: Ludwigsburg Gruenbuehl, Stuttgart, Germany, *Google Maps,* 2023)

Experimental ice store at the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) at the University of Stuttgart (Germany) with a water volume of 10 m³ and heat exchangers e.g. for testing sensors to determine the state of charge (Source: IGTE)

Ice store under construction with a volume of 560 m³ for supplying heating and cooling to an urban district (Source: https://www.cleanthinking.de/eisspeicher-sorgt-fuer-kaelte-und-waerme-im-quartier/)

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3.3 Thermochemical Storage – Closed Adsorption

Thermochemical storage technologies enable the local and temporal decoupling of the generation of heat and its use. As the energy is not stored as sensible heat, but through spatially separated reactants of an exothermal reaction, there is no temperature difference between the charged storage and the ambient. Consequently, the heat can be stored almost loss-free, even over long periods of time. In addition, comparatively high storage densities can be achieved [1]. As part of the *Heat2Share* project this storage technology is being used to enhance the efficiency of a municipality's heat supply.

Process of thermochemical storage: Closed adsorption

This thermochemical storage technology uses the principle of adsorption and desorption. In this process, a substance – often water – is adsorbed onto a sorbent, releasing heat, and desorbed again when heat is added. Figure 1 illustrates the operation mode of a thermochemical storage system: During discharging, liquid water is vaporized by supplying heat at a low temperature level. Subsequently, it flows through an unloaded sorption bed, which adsorbs the water vapor. Adsorption enthalpy is released in form of heat at a high temperature level. During charging, heat at a high temperature level is supplied to the sorption bed, causing the adsorbed water to vaporize again. This water vapor is condensed, releasing heat at a low temperature level. The water as well as the sorption material are spatially separated during the charged state. Since during charging or discharging the same water is continuously condensed and evaporated while the heat transfer is provided by a secondary fluid there is no mass exchange with the ambient, this process is referred to as closed adsorption [2].

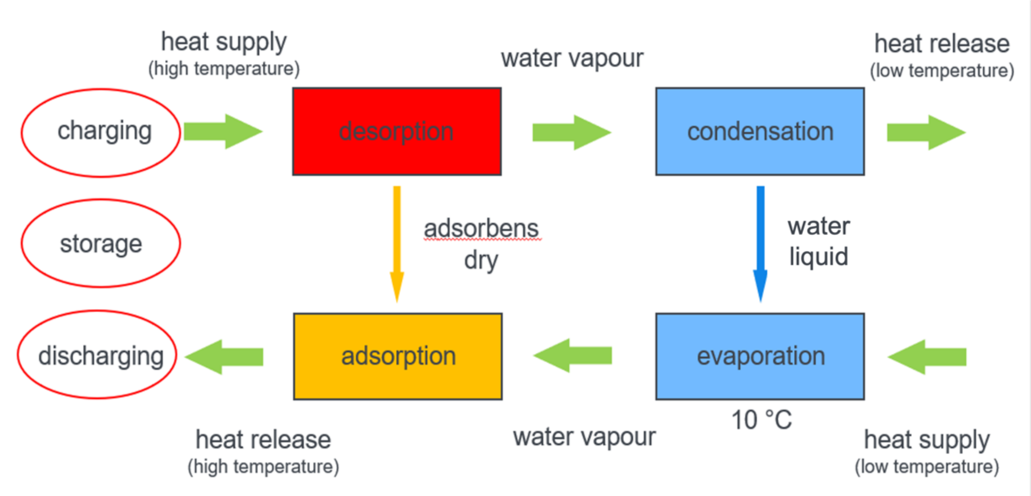

Figure 5: Mode of operation of a thermochemical storage adapted from [3]

Structure of the storage

A thermochemical storage system comprises at least one sorption bed with an integrated heat exchanger, a condenser, a water supply vessel and an evaporator. During charging, heat is supplied to the sorption bed via the heat exchanger. The consequently released water vapor is condensed in the condenser, and the liquid water is fed into the water vessel. During discharging, water from the vessel is vaporized in the evaporator, and subsequently passed through the sorption bed. The released heat is dissipated via the heat exchanger.

In order to flexibly adapt the heat provided by the storage system to the heat demand, a modular storage system is being constructed as part of the Heat2Share project (see 'Examples'). Each module consists of two sorption beds, an evaporator, a water supply vessel and a condenser. The configuration of such a module is shown in Figure 2. A storage system consisting of two modules was built for an application in a local heating network. Each sorption bed contains 250 kg of sorbent, resulting in a total of one 1000 kg of sorbent being utilized. The charging and discharging power ranges from 16 – 25 kW for the whole system. Depending on the heat demand and heat surplus, a corresponding number of sorption beds can be flowed through [4].

As sorbent a composite of active carbon and calcium chloride is used. This provides a high storage density at low operating temperatures, a high adsorption enthalpy, fast sorption kinetics and a high cost efficiency referred to the production of high quantities. However, it is corrosive, resulting in special demands for the storage systems [5].

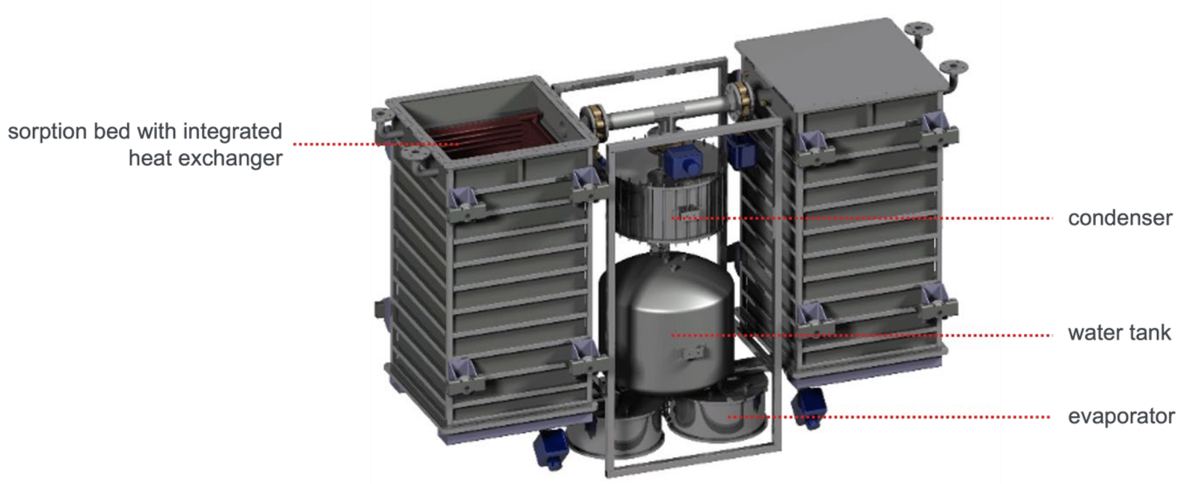

Figure 6: Illustration of one module of the Heat2Share storage system. The module comprises two sorption beds, an evaporator, a water supply vessel and a condenser

3.3.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

- renewable energy generation
- heating and or cooling
- thermal energy storage
- electrical energy storage
- building construction/renovation
- energy self-resilience
- thermal comfort

3.3.2 Examples

As part of the project *Heat2Share*, the described technology of the thermochemical storage is integrated into the local heat grid of the municipality of Barenthin, Germany. In the existing heat supply grid, 29 building units are supplied by a combined heat and power plant (CHP), which is connected to a biogas plant. The CHP has a thermal gross output of 420 kW and an electrical gross output of 360 kW, with an annual heat demand of 1100 MWh. At midday and at nighttime, the plant provides excess heat, which is currently released to the atmosphere without being used. Often, the direct use of the heat from biogas plants is only possible at limited extend due to its relatively low temperature level, significant fluctuations in heat excess, or seasonal mismatch with the heat demand. Thermochemical storage is intended to address these challenges by storing the excess heat and covering peak loads during the morning and evening hours. For this purpose, the heat generated during electricity generation is directed to the storage units described. This process is shown schematically in figure 3 [4].

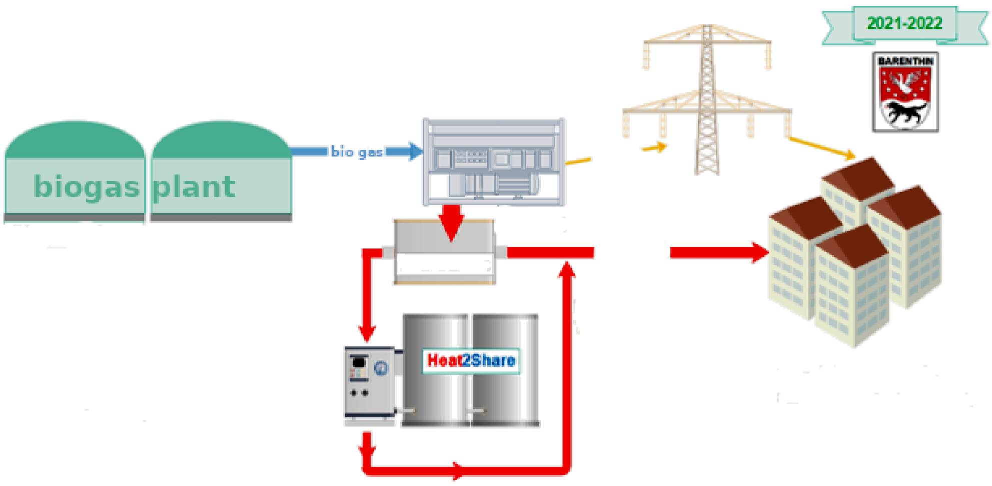

Figure 7: heat and electricity supply after the integration of a thermochemical storage

In this way, the stored heat can be fed into the heat supply grid of Barenthin twice a day at the return temperature (55 °C).

Both the electricity production – and thus heat supply – of a CHP varies over the year and the time of day, as does the demand for heat. Through the modular control of the heat storage system, heat can be fed in and distributed to building units according to supply and demand requirements [4].

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3.4 Thermal storage with vacuum insulation

The thermal storage technology with vacuum insulation relevant for Solar Energy Buildings are hot water stores. Currently there are two main vacuum insulation technologies for hot water stores on the market.

The first technology comprises of standard insulation materials supplemented by bendable vacuum insulation panels (VIP). VIP provide around 10 times lower thermal conductivities than conventional insulation materials, however the price is around 30 times higher. In figure 1 VIP are shown and an example for the composition of the insulation technology is shown in figure 2. This insulation technology is currently available on the market mainly for hot water stores up to 1 m³ and has been developed for hot water stores up to 2 m³ water volume within the research project “Sol4City” [Sol4City 2019]. The thermal losses of a hot water store using this insulation technology is dependent on the VIP share used within the insulation. This insulation technology is usually applied to reach a certain energy efficiency class of the EU Ecodesign Directive while maintaining an applicable total insulation thickness.

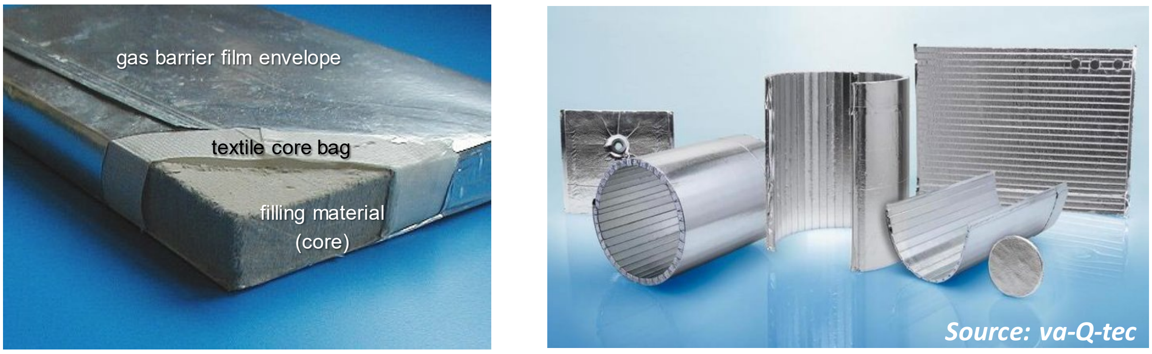


Figure 1: Vacuum insulation panels (VIP). Left: Composition of a VIP [Erb 2005] (modified by the author); right: different forms of bendable and unbendable VIP.

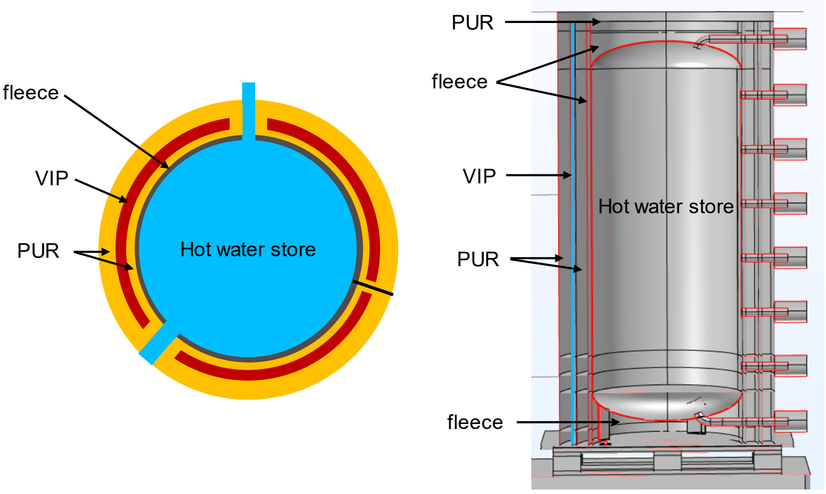


Figure 2: Sketch of an example for the composition of a hot water store with vacuum insulation by bendable VIP. Left: sectional top view; right: half-sectional front view. PUR: rigid polyurethane foam. VIP are non-detachable included in the PUR foam.

The second vacuum insulation technology is a double-walled hot water storage tank, where the gap between the walls is usually filled by a powder and then evacuated, see figure 3. Instead of the powder filling there is also the possibility to insert a multi-layer insulation (MLI) of infrared-reflective foils kept in distance mostly by a textile material or to leave the space empty, while having infrared reflective wall surfaces [Sutheesh 2018], [Bo 2021], [Gottschald 2014], [Vakutank 2019]. However, the latter two options are to the best of the authors knowledge currently not market-available for hot water stores. Double-walled hot water stores with vacuum insulation can reach up to 10 times lower heat losses than conventionally insulated hot water stores with the same size, insulation thickness and temperatures. This technology is profitable mainly for storage volumes ≥ 5 m³. Due to the bigger size, the very high insulation performance and the hermetic enclosure of the whole insulation, this technology is perfectly suitable for outdoor installation, where the hot water store doesn’t consume valuable indoor space. Thus, it is a promising method for the installation of big thermal storage capacities for existing buildings. [Gerschitzka, 2016], [Beikircher, 2013]

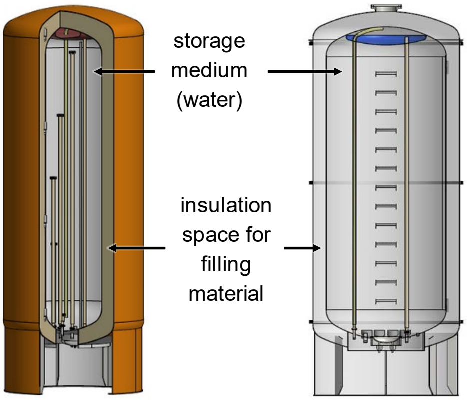


Figure 3: Schematic depiction and CAD drawing of double-walled hot water stores with vacuum insulation [Sirch 2024], [Gerschitzka, 2016] (modified by the author).

Conventional insulation materials are porous and trap gas into small pores to prevent convection of the gas. Convection is a heat transfer mechanism that causes high heat losses. Without convection a thermal insulation can take advantage of the comparably low thermal conductivity of the gas. Thus, the heat transfer mechanisms in conventional insulation materials are:

- thermal conduction via the solid phase
- thermal conduction via the gas phase
- thermal radiation

In open-pored insulation materials, the filling gas is the atmospheric air. In close-pored foams, such as rigid polyurethane foam (PUR), a gas with a lower thermal conductivity than air can be trapped in the pores during the manufacturing process. In PUR e. g., mostly pentanes (iso-, cyclo-, …) in a mixture with CO_2 are used. Thermal conduction via the gas phase plus coupling effects of solid and gas conduction are at temperatures between 10 °C and 100 °C usually responsible for the by far biggest share of the total heat transfer via a conventional insulation material. Vacuum insulation aims to eliminate this part of the heat transfer by evacuation of the gas. Thus, vacuum insulation usually reaches around 5 – 10 times lower thermal conductivities than conventional insulation, dependent from the filling material of the vacuum insulation, the type of conventional insulation material and the temperature, see figure 4.

In the vacuum insulation of double-walled hot water stores the first function of the filling materials is the mitigation of thermal radiation. Filling materials usually do this more effectively than infrared reflective coatings of the inner sides of the walls [Gerschitzka, 2016]. The second function is to increase the vacuum pressure necessary to eliminate significant thermal conduction via the gas phase. The lower the mean pore size of the filling materials, respectively the distance of the walls the gas is trapped in, the higher is this vacuum pressure. This effect is called Knudsen effect or Smoluchowski effect, named after the main researchers of this phenomenon. Higher vacuum pressures are easier to reach and to maintain. Whereas in double-walled hot water stores the walls are rigid enough to stand the atmospheric pressure, in VIP, where thin foils maintain the vacuum pressure, the filling material has also the function to maintain the shape of the insulation by its pressure resistance.

In double-walled hot water stores usually expanded perlites are used as filling material. In VIP mostly a mixture of fumed silica, silicon carbide and glass or plastic fibers are used. VIP usually have higher leakage rates than double-walled steel tanks. Thus, a filling material with a lower mean pore size is necessary. That is granted by the fumed silica, providing a lower mean pore size but also higher costs than expanded perlites. The thermal conductivity of most VIP can be expected to be approximately doubled after 25 years due to leakage [Schwab 2004]. Other than VIP, the insulation space of double-walled tanks can be re-evacuated if a significant increase of gas pressure and heat losses is detected.

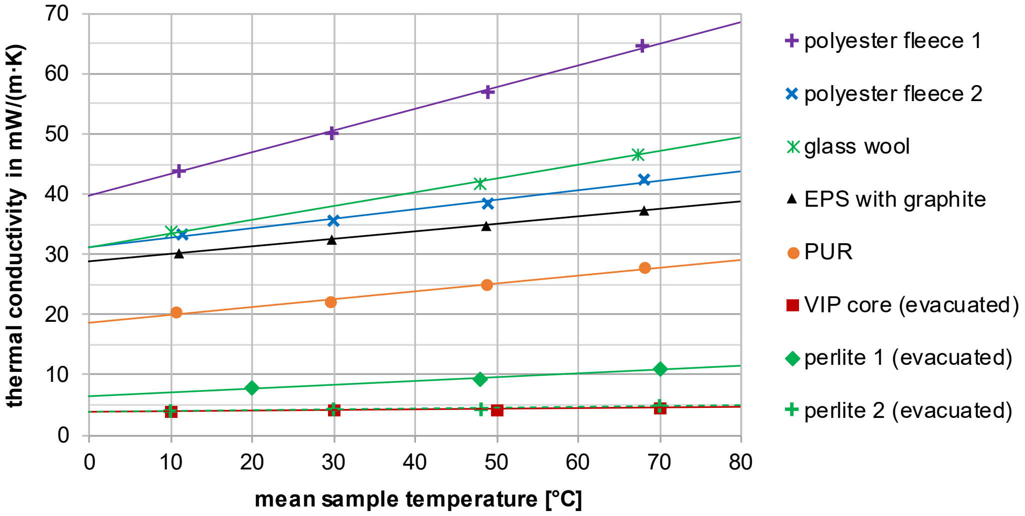


Figure 4: Thermal conductivity as a function of the temperature of conventional insulation materials and vacuum insulation common for hot water stores. Straight lines are linear inter- and extrapolations of the measuring points. EPS: expanded polystyrene. Data sources: [IGTE 2024], [Urbaneck 2018], [Morgan 2017], [Lang 2022]

3.4.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

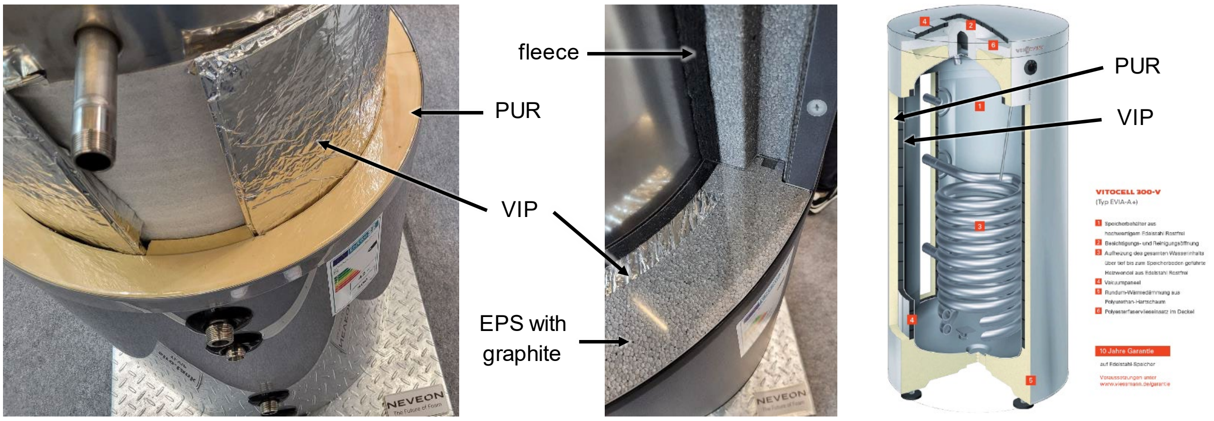
thermal energy storage

thermal comfort

electrical energy storage

3.4.2 Examples

Double-walled vacuum insulated hot water stores by the manufacturer Sirch. Left: hot water store with 60 m³ water volume, installed at a public pool in Neumarkt (Germany), driven by combined heat and power plants (CHP); middle: hot water store with 8 m³ water volume, installed inside a new-built private dwelling in Kirchdorf (Austria); right: hot water store with 12 m³ water volume and additional transparent thermal insulation (glass), installed at an outdoor test rig of the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) of the University of Stuttgart. Pictures made by IGTE.



Vacuum insulated hot water stores with VIP. Left and middle: exhibits of the composition of a vacuum insulation with VIP for hot water stores by Neveon (Pictures by IGTE); right: hot water store "Vitocell 300-V" by Viessmann [Viessmann 2020]. Left and right: non-detachable insulation, middle: detachable insulation.

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3.5 Battery Energy Storage System

Battery Energy Storage Systems (BESS) offer multiple benefits to buildings utilizing Photovoltaic (PV) generation. One advantage is the potential for increased solar load cover factor in buildings equipped with BESS. This feature not only boosts renewable energy usage but also enhances the resilience and reliability of the building's energy supply [1]. Even if PV systems produce power peaks during high electricity demand, the energy might not be fully consumed by the building immediately. The Battery Energy Storage System (BESS) harnesses surplus solar energy, storing it for future use and promoting solar power integration within the building.

This capacity to store surplus energy has two major consequences. Firstly, it can significantly decrease the grid load, especially beneficial during peak demand periods when the grid is most strained [2]. Secondly, it can augment the building's self-consumption rate. Therefore the building can rely more on its own generated energy rather than drawing from the grid. [3]

If grid limitations restrict the size of installed solar panels (PV), Battery Energy Storage Systems (BESS) can facilitate larger PV installations due to their ability to manage the generated power. In Figure 1 a solar energy building with BESS is shown.

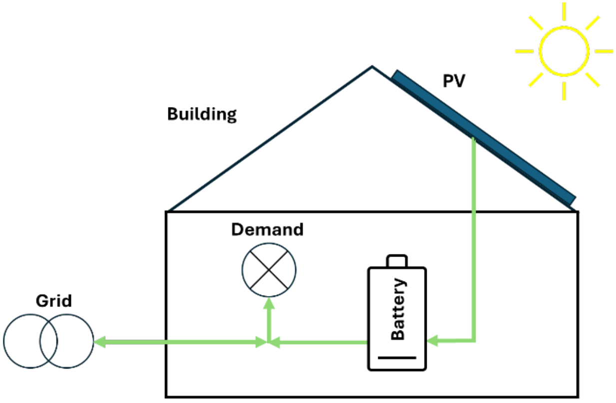

Figure 8: Schematic of a solar energy building using BESS

Adding a BESS allows buildings to adjust their energy use based on their needs. This added flexibility is a great benefit, making it possible to use advanced control techniques like model predictive control. These control strategies help buildings to manage their energy use in real time, reacting ahead of time to shifts in energy demand and use the solar power output as efficient as possible. As a result, the integration of a BESS not only enhances operational efficiency but also lays the groundwork for more intelligent and adaptive energy management systems within buildings.

The economic feasibility of a BESS for PV storage is largely dependent on two factors: the cost of the battery and its operational lifespan. The cost of the battery, in turn, depends on the type of battery used. For residential buildings, the most relevant types of batteries are Lithium based Batteries and Lead Acid Batteries [4].

Lithium based Batteries are generally preferred over Lead Acid batteries, despite their higher initial cost, because they provide a higher energy density, meaning they can store more energy per unit of size. They also demonstrate superior efficiency, leading to less energy being lost during the charging and discharging process. Moreover, their extended service life ensures they can function effectively for a greater duration compared to other battery categories. In fact, a Lithium-Ion battery lasts around three times longer than a lead acid battery. [5] These factors play a crucial role in mitigating the initial higher purchase cost, thereby solidifying the position of Lithium-Ion Batteries as a preferred choice for Battery Energy Storage Systems (BESS) in residential buildings [6].

The ongoing trend of decreasing lithium-ion battery prices is anticipated to further enhance their competitiveness compared to lead-acid batteries [7]. Decreased costs make BESS more accessible for residential use. This benefits homeowners by allowing them to consume more of their own energy and helps the grid by reducing the load.

3.5.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

electrical energy storage

energy self-resilience

3.5.2 Examples

In Reidberg, Germany, a five-story multi-family building built in 2015 achieves self-sufficiency of 26% for heating, 100% for cooling, and 42% for electricity. It incorporates photovoltaic modules on the roof (84 kWp) and façade (15 kWp), along with a 59.4 kWh integrated battery system. Surplus energy charges electric vehicles in the shared underground car park.

Figure 9: Example for a solar energy building with BESS (Source: Datei:Energiehaus Plus Frankfurter Riedberg Constantin Meyer).jpg – Wikipedia *[8])*

The building shown in Figure 10 was finished in 2018 and has a PV power of around 29,6 kWp. The battery storage capacity is around 46 kWh. The yearly electricity consumption is expected to be around 16900 kWh and the solar coverage ratio is around 75%. [9]

Figure 11: Example for a multifamily solar energy building with BESS (Source: TU Bergakademie Freiberg [10])

Each of the example buildings in Figure 4 has 58 m^2 of PV installed with results in around 8,4 kWp. The battery storage system has a capacity of 58 kWh. The yearly electricity demand is around 2000 kWh/a. The solar coverage ratio tends to be above 90 % in the most years. [11]

Figure 12: Example for two solar energy buildings with BESS (Source: TU Bergakademie Freiberg [10]*)*

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3.6 Sorption Heat Storage - SolSpaces

The SolSpaces sorption heat storage system, developed by the University of Stuttgart, enhances energy efficiency in heating systems and promotes the use of renewable energies. This system utilizes evacuated-tube solar air collectors to efficiently capture thermal energy. Its innovative design features segmented storage volumes, allowing for the use of large amounts of storage material, increasing the capacity of the system and without long-term losses. Typically, sorption heat storage systems can store up to three times more energy than conventional hot water storage systems (Luca Scapino et al. 2017).

Characteristics of Sorption Heat Storage

Capacity and Design: The storage unit has a total volume of 4.3 m³ and a theoretical storage capacity of approximately 700 kWh. It is divided into four quadrants, each containing six segments with 177 liters of zeolite. This configuration, shown in Figure 1, is designed to minimize pressure loss through the zeolite bed, thus optimizing system efficiency (Weber et al.).

Control Mechanism: A sliding system allows for individual control of each segment pair by selectively opening or closing the corresponding air aperture to effectively manage airflow direction (Weber et al.).

The Figure 1 Prinzip der Sorptionswärmespeicherung.

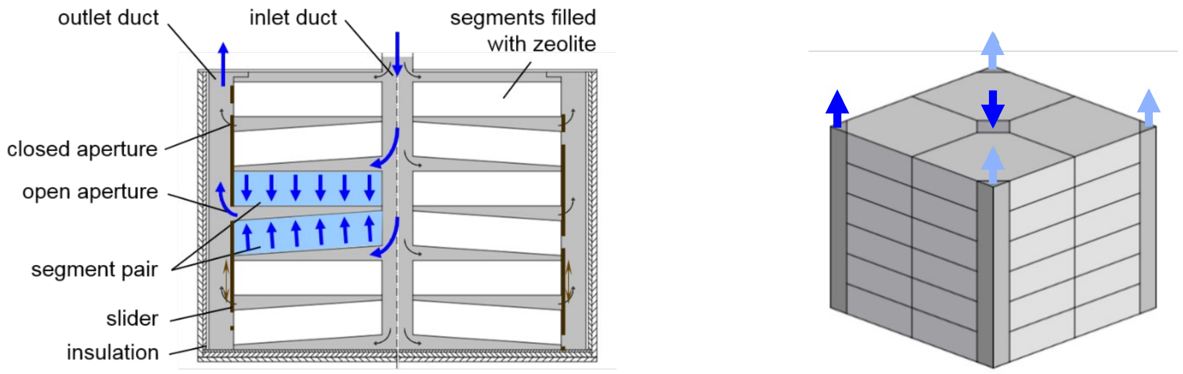


Figure 1: Schematic of segmented sorption heat storage (right) and vertical cross-section (left).

Operating Principle: Adsorption and Desorption

The system operates on the principle of adsorption, where water vapor molecules in the air attach to the surface of a solid, porous material such as zeolite, releasing heat. Once the material is saturated, it undergoes desorption, which involves heating to release water and dry the zeolite, thereby allowing for efficient and repeatable heat storage and release.

Operating Modes:

1. Heating with Solar Collectors: During the heating season, if solar radiation is sufficient, air is heated using evacuated tube collectors to warm the building.
2. Heating with Sorption Heat Storage (Adsorption): When solar radiation is insufficient, building air passes through the sorption heat storage. Here, it adsorbs moisture and releases heat for heating purposes.
3. Regeneration of Storage (Desorption): If there is excess solar radiation, the air is heated in the solar collector and then used to dry the material in the heat storage, preparing the system to heat the building again.

The operating modes are shown in Figure 2 (Weber et al. 2016).

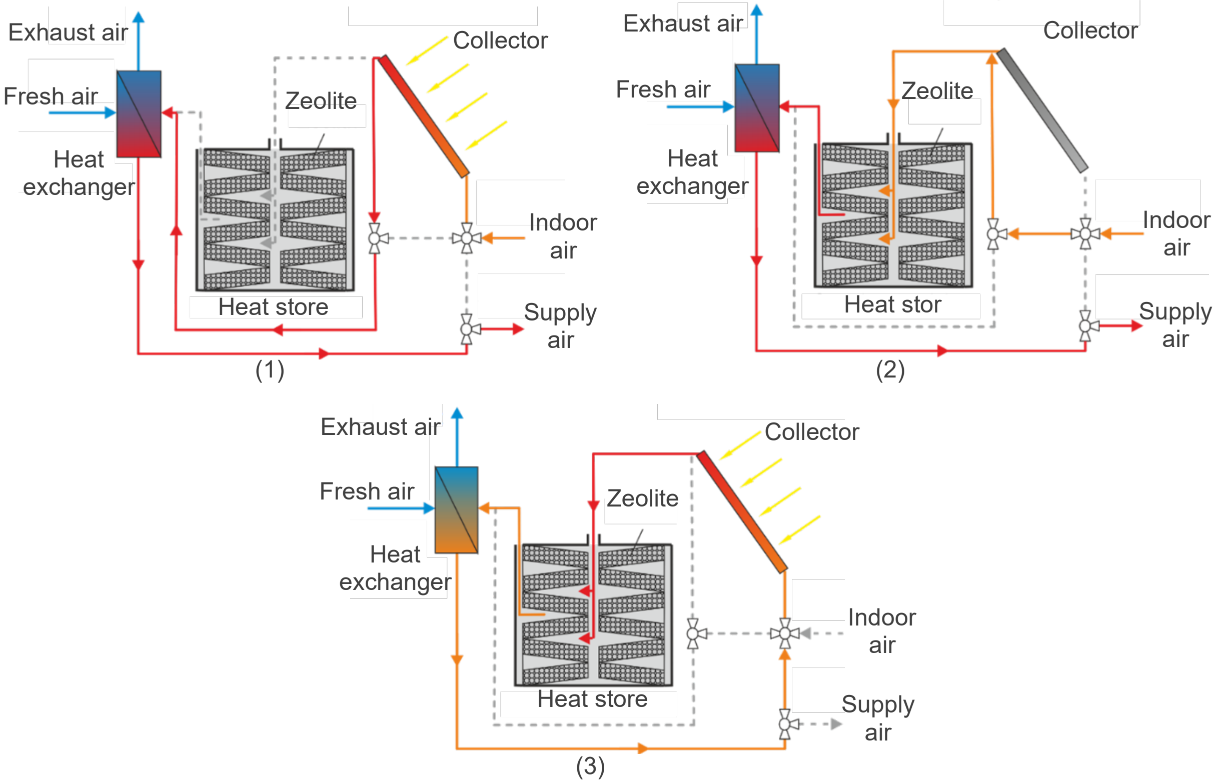


Figure 2: Operating modes of the solar heating system: (1) Heating with solar collector, (2) Heating with sorption heat storage (Adsorption), (3) Regeneration of the sorption heat storage (Desorption).

Benefits of Segmentation:

- Reduced Pressure Loss and Enhanced Fan Efficiency: The segmentation design shortens flow paths and increases cross-sections, minimizing pressure loss and improving fan efficiency.
- Enhanced Desorption Efficiency: Segmentation enables individual areas to be heated to high temperatures effectively, overcoming challenges related to the heat capacity of the entire storage unit or significant heat losses in large volumes.
- Quicker Heat Availability: By dividing the system into smaller units, heat can be generated more rapidly due to more efficient utilization of adsorption enthalpy.
- Flexible and Targeted Heat Release: Segmentation permits heat release to be finely adjusted according to demand, enabling more precise control.

(Weber et al. 2016)

Summary

In summary, the sorption heat storage developed in the SolSpaces project at the University of Stuttgart marks a significant advancement in thermal storage technology Its segmented design notably enhances thermal performance, enabling efficient management and utilization of large material volumes. This progress provides effective and adaptable solutions for building heating with renewable energy, representing a significant step forward in sustainable building technology.

3.6.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

thermal energy storage

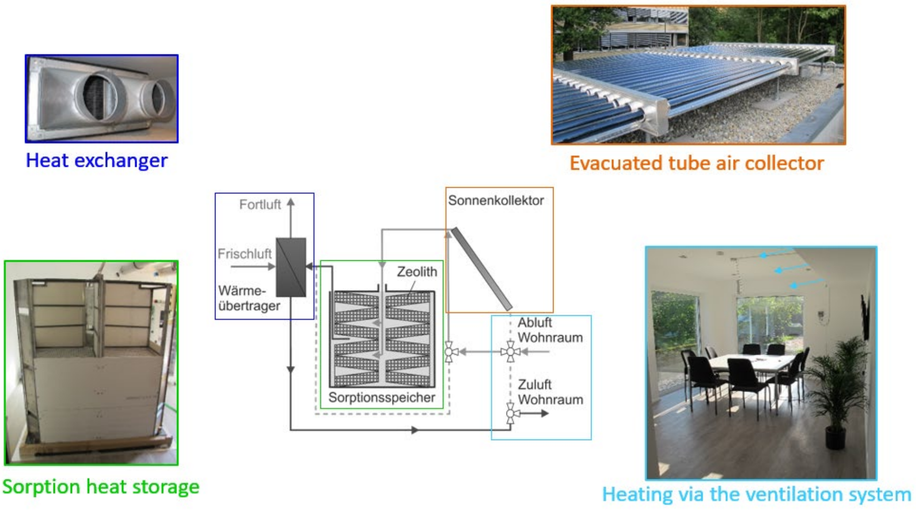
thermal comfort

building construction/renovation

energy self-resilience

electrical energy storage

3.6.2 Examples



SolSpaces: Setup of a solar thermal heat supply system with sorption heat storage for energy efficient compact buildings [1].

SolSpaces: Test facility at the University of Stuttgart [1]

[1] The image was provided by the Institute for Building Energetics, Thermotechnology and Energy Storage. For more information about the Institute, please visit their homepage at [https://www.igte.uni-stuttgart.de/forschung/abgeschlossene/solspaces/]

3.6.3 Sources

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3.7 Mine thermal energy storage

Storage technologies are essential in order to optimise the use of renewable energy sources. One option for storing large amounts of heat and/or cold over a longer period of time, in addition to utilisable aquifers, could be disused, uncapped and flooded ore and coal mines (Mine Thermal Energy Storage MTES). (Jessop et al. 1995; Grab et al. 2018) Particularly high storage temperatures of more than 50°C theoretically increase the potential for utilisation, but can also result in increased technical and legislative risks and costs (Fleuchaus et al. 2020). The flooded mine workings are characterised by artificially created cavities with high anisotropic water permeabilities between caverns, shafts and tunnel systems. In combination with the resulting large heat-transferring surfaces, the old mines represent very large heat storage potentials that can be utilised with a wide variety of utilisation concepts for heating and cooling buildings (Grab et al. 2018).

Figure 1 shows two possible setups for a mine water thermal energy storage. In the picture (left), the same mine area is used for heat extraction and storage (A), e.g.:

- Storage period (mainly summer): Excess heat, e.g. from solar thermal energy or industrial waste heat, is transferred to the mine water via heat exchangers. This heats up and releases heat to the surrounding rock.
- Withdrawal period (mainly winter): The heat is extracted from the mine water; any heat stored in the rock flows back into the mine water and can thus also be utilised. In most cases, the temperature level for the heating application must be raised with a heat pump.

This principle can also be used to store heat in flooded natural cavities, such as caves. The disadvantage of this variant is that it is only possible to store or release heat, i.e. heat and cold cannot be released to potential consumers in combination. This is possible with the scheme shown in Figure 1 on the right. There are two areas in the mine, a warm area (B) and a cold area (C):

- If cooling is required or heat is to be stored, mine water from the cold area is used, heated in the heat exchanger and then released to the warm area
- If heating is required or heat is to be stored, the warm mine water is utilised, cooled in the heat exchanger and then released to the cold area.

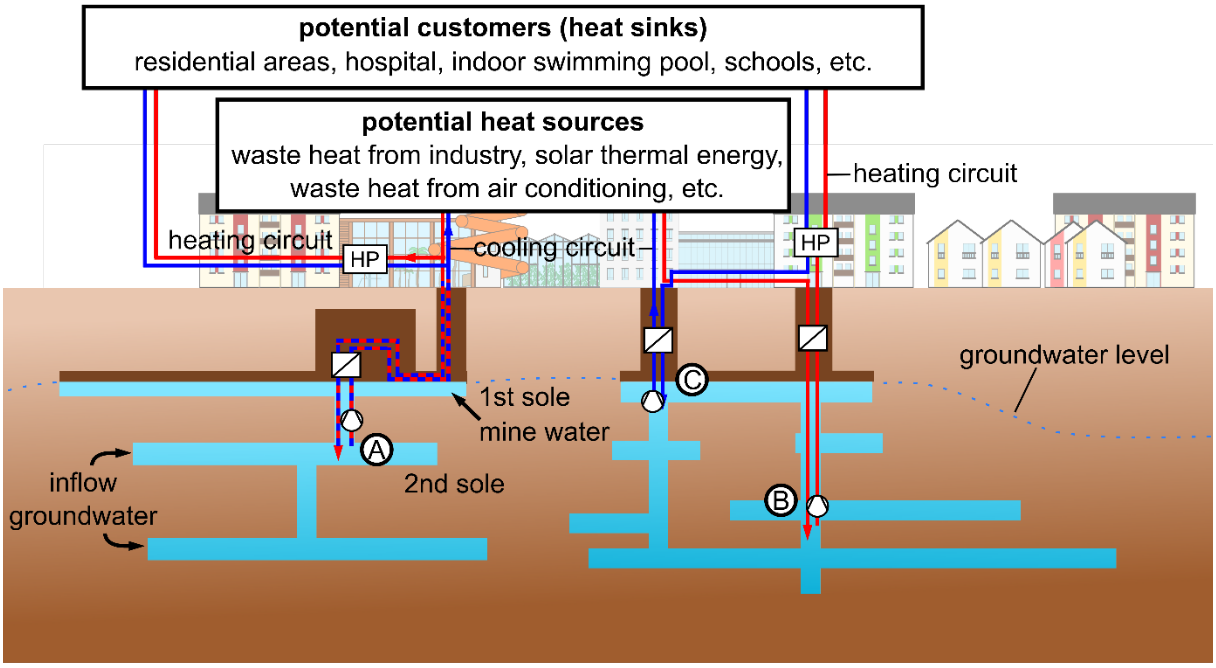

Figure 1 Schematic structure of a possible seasonal heat storage facility in abandoned and flooded mines (combined warm/cold storage basin (A), separate storage facility with warm (B) and cold (C) areas)
Source: Lukas Oppelt, TU Bergakademie Freiberg (own illustration)

This separation provides more options for controlling and operating the storage facility. Due to their good thermal properties, heat storage systems in flooded mines or caves have the potential to be used as seasonal long-term heat storage systems in the future. The growth of intermittent renewable energy generators and CHP plants, as well as rising energy prices, are increasingly focussing on large-scale storage systems for load balancing. MTES can fulfil this task, but there are also certain risks. Firstly, the possible locations for such storage facilities are very limited, as they require flooded disused mines or corresponding natural structures. In locations where the construction of an MTES is possible, these are to be favoured over other geothermal heat storage systems in terms of storage potential and charging capacity. Particularly in the case of a very large consumer structure, MTES prove to be advantageous due to their low specific storage costs. If, on the other hand, the heat consumption volume is only low or there is a high level of structural uncertainty, smaller, lower-investment storage types are preferable. The technology has also not yet been tested on a large scale in continuous operation. Another problem could be the formation of fouling deposits in the heat exchanger, which significantly reduces efficiency (Oppelt et al. 2021). Previous tests have shown a storage efficiency of around 50 %. (Schaberg 1998). Two model projects are presented in the examples. These also deal with the optimised design of heat transfer systems.

3.7.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

energy self-resilience

thermal energy storage

3.7.2 Examples

Reiche Zeche Freiberg

For the MineATES project, part of the Reiche Zeche mine in Freiberg (Germany) was flooded in order to carry out various tests. For example, a mobile heat pump test rig is used to introduce temperature anomalies in order to track the spread of heat or cold input into the mine workings. Mine water is used as the heat source, which is channelled to the test site from another level. In addition, various designs (different materials and coatings) for plate heat exchangers are also being trialled in order to increase the efficiency of the system by reducing fouling deposits in the heat exchanger.

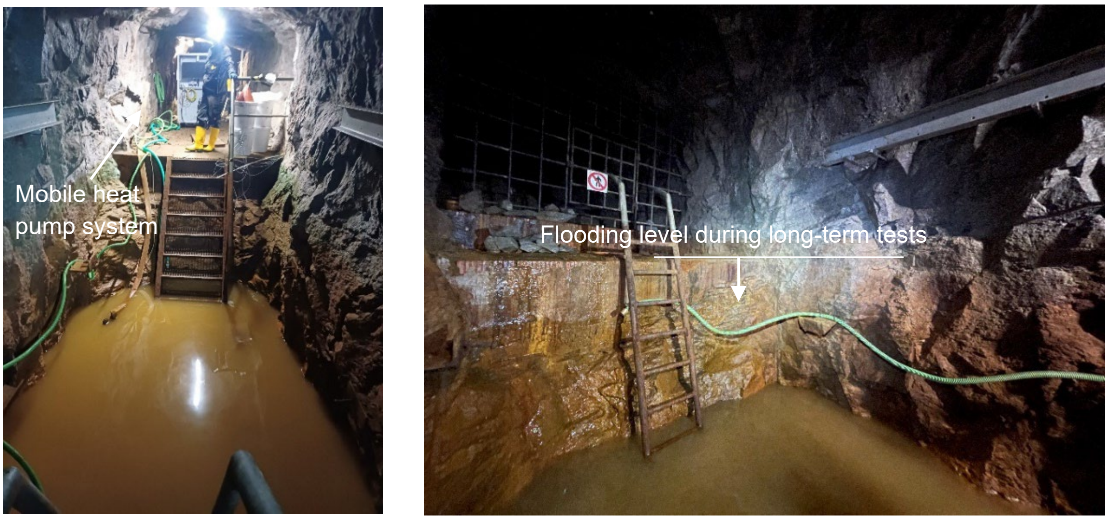

Figure 13 Installation of the test facility in the Reichen Zeche Freiberg mine

Fraunhofer mine Bochum

On the site of the Fraunhofer IEG in Bochum (Germany), a former flooded small mine was drilled into and solar yields from a concentrating solar thermal system are being stored. The aim of the WINZER research project is to demonstrate the potential and challenges of mine heat storage systems in urban centres with various non-ideal boundary conditions by means of very comprehensive condition monitoring. To this end, scientific issues relating to thermo-hydraulics (simulation and tracers), the potential for mobilising pollutants, hydrochemistry, microbiology with a focus on biofouling, scaling and corrosion under changing thermal storage conditions, the reduction in efficiency at the above-ground facilities in cyclical load behaviour, as well as rock mechanical effects, e.g. uplift, subsidence and mining damage during operation at a pilot site are being investigated in detail.

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3.8 Large scale sensible storage

Solar energy, as a pollution-free, inexhaustible, and affordable energy resource, has received extensive study and numerous applications throughout the world. However, one of the longstanding barriers to solar energy technology lies in the noticeable misalignment between energy supply and consumption. Therefore, the energy storage concept is proposed as an essential way to address the mismatch.

The idea of thermal energy storage (TES) was first mentioned and investigated to address the energy shortage crisis in the 1970s. By means of energy storage, intermittent solar energy can not only meet the demands of space heating and domestic water supply but also to offer a high-grade heat source all year round regardless of timing or seasonal constraints.

Energy storage can be classified into short-term storage and long-term storage according to different storage durations. Using excess heat collected in the summer to compensate for the heat supply insufficiency during the wintertime is the concept of seasonal thermal energy storage (STES), also called long-term heat storage. The storage can be short-term (diurnal) and long-term (seasonal). The seasonal storage has greater potential in practical applications, it is more technologically challenging than short-term storage. It requires large storage volumes and has greater risks of heat losses, and the material chosen for implementation must be economical, reliable, and ecological. Sensible heat storage comprises water tank storage and underground thermal energy storages UTES. The major methods employed for UTES include aquifer storage and underground soil storage.

The sensible heat storage method converts collected solar energy into sensible heat in selected materials and retrieves it when heat is required. The stored heat amount is determined by the specific heat of the material and its temperature increase. Sensible heat storage is a simple, low-cost, and relatively mature technology for seasonal energy storage compared to the other alternatives. Due to its feature of inexpensive and reliable, it has been implemented in a significant number of projects. Specific heat capacity and density are regarded as two critical indices by which one of the major storage evaluation criteria. Existing large-scale seasonal storage projects involving water-based storage, rock (mostly using gravel) storage and ground/soil storage. Water is considered to be a favourable material for energy storage due to its high specific heat (compared with other sensible heat storage media) and high-capacity rate while being charged and discharged. Water-based storage systems literally employ water as the storage medium or heat carrier fluid for storing/transferring heat. They can be further classified into water tank and aquifer storage systems. Water tank/pit storage systems store water in an artificial structure, whereas aquifer storage uses natural water directly from the underground layer.

Water tank systems

Water tanks are artificial structures that are made of stainless steel or reinforced concrete surrounded by thick insulation. They are usually buried underground (also called water pits) or placed on the roof or outside of a building (Bauer et al., 2010). Water storage tanks operate in a stratified manner with water at the top of the tank being hotter than that in the bottom due to thermal buoyancy, and the subsequent mixing effect caused by the temperature difference may degrade the heat source level and negatively impact the system efficiency. To minimise such a phenomenon, many studies have investigated methods for maintaining the inside water in a stable thermal stratification status. In addition to the studies on the optimisation of stratification status, another popular research area in water tank storage lies in the reduction of heat losses during the heat storage process. Efforts have been made in tank design and selection of insulation materials. Glass wool and polyurethane are widely used insulation materials. As shown in Figure , stainless steel or high-density polyethylene layers placed on the roof and the vertical inside part of the tanks are used as liners to reduce heat losses resulted from vapour diffusion through the concrete wall. In a project in Hannover (Lottner et al., 2000), a granulated foam glass filled into textile bags was employed between the soil and the high-density concrete (HDC) wall of an artificial tank.

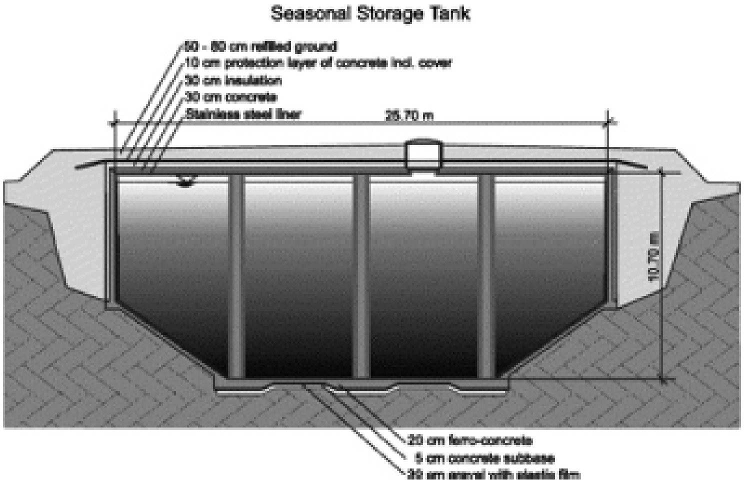

Figure 14 4500-m3 hot water storage tank in Hamburg-Bramfeld. (Lottner et al., 2000).

Solar District Heating (SDH) systems use solar thermal technology to produce hot water for district heating networks, reducing reliance on fossil fuels and contributing to decarbonisation efforts in communities and cities. Well-established in Europe, particularly in Northern countries like Denmark, SDH holds significant potential to further decarbonise heat across diverse regions. Currently, several large SDH systems are under construction in different countries, including Germany, the Netherlands, Serbia, and Kosovo. These initiatives are a testimony of the increasing adoption of solar thermal technology, marking important steps towards heating decarbonisation across Europe. Figure presents a schematic layout of a seasonal hot water heat store system in Friedrichshafen, Germany (Raab et al., 2004), with 12,000-m3 store with an additional inner stainless-steel liner for heat loss reduction was built, and 3513-m2 integrated roof collectors were constructed on top of a multi-family building to provide energy for the water tank. This storage unit was connected to a district heating system.

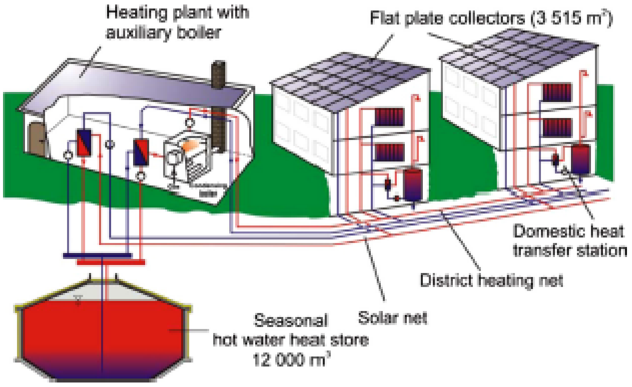

Figure 15 District heating system (Raab et al., 2004)

Aquifer systems

Aquifer storage is referred to as a “promising cost-effective option” for seasonal storage. The idea of aquifer thermal energy storage (ATES) was first launched in 1976 and has frequently been used in practice.

In an ATES for seasonal heat storage, a suitable aquifer into which at least two thermal wells (one is called the hot well and the other the cold well) should be drilled is required. The aquifer geologic formation is used as the storage medium, whereas groundwater is employed as the heat carrier fluid. Because of the features of the porous media and the high specific heat capacity of water, an aquifer is a capable medium where heat can be stored and retrieved. During the charging process, ground water is produced from the cold well, heated by solar energy and then injected into the warm well. During the discharging phase, the flow reverses. Negative impacts on the groundwater system may be caused if the preliminary study is not sufficient, and the reliance on hydro-geological conditions makes aquifer storage quite complex and conditional. In addition, because it is impossible to install heat insulation for an aquifer store, the heat loss problem should be carefully dealt with.

Rock beds

In rock bed heat storage, the rock (pebble, gravel or bricks) bed is usually circulated with a heat transfer fluid (water or air) to exchange heat (gained in summer and released in winter). Compared to water-based systems, rock-based systems can endure much higher temperatures.

Due to the low energy density, rock bed storage systems require much larger volumes to achieve the same amount of heat storage, approximately three times (Dincer and Rosen, 2002) more space than water-based storage systems. Some researchers developed a gravel/water (pebble/water, sand/water) storage system by combining the concepts of water tank and rock storage, which can be viewed as a compromise between the high water tank construction expenses and the low thermal capacity problems of rock materials. A gravel-water mixture can slightly reduce the volume of the storage unit yet is still approximately 50%larger than a hot-water heat store in achieving the same heat capacity (Schmidt et al., 2004).

Ground and soil storage

Ground/soil storage is another application of UTES aside from aquifer systems. There is no need for a separated site because the ground itself is used directly as the storage material. The underground structure can store a large amount of solar heat collected in the summer for later use in winter. In this storage approach, the ground is excavated and drilled to insert vertical or horizontal tubes, so it is also called borehole thermal energy storage (BTES) or duct heat storage in some literatures (Schmidt et al., 2003). The inserted tubes serve as heat exchangers, the free soil is the storage medium. However, a BTES system requires 3 to 5 times more volume to carry the same amount of heat as the hot-water storage system due to its lower energy storage density. Small power rate caused by heat transfer in the borehole is another short come of the system; thereby, an auxiliary water buffer store unit is usually necessary in a large-scale plant. To provide good thermal contact with the surrounding soil, the space between the pipes and the borehole wall is usually filled with high thermal conductivity grouting material in order to enhance heat transfer. Although the BTES concept has received considerable attention due to its potential for large-scale applications, it has several drawbacks: high initial cost, complexity of the underground conditions of water

3.8.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

thermal energy storage

heating and or cooling

energy self-resilience

electrical energy storage

3.8.2 Examples

Figure 16 Jenni Energietechnik AG solar tanks.

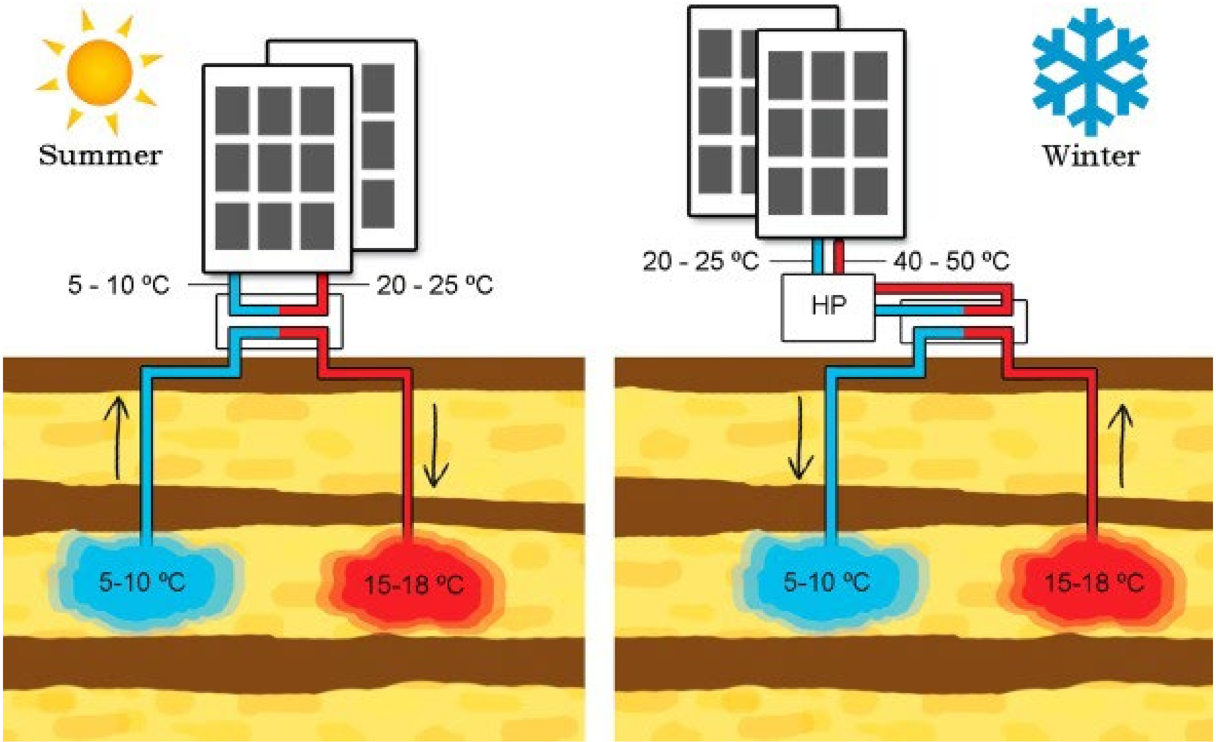

Figure 17 Working principle of Aquifer Thermal Energy Storage (Rostampour et al., 2019).

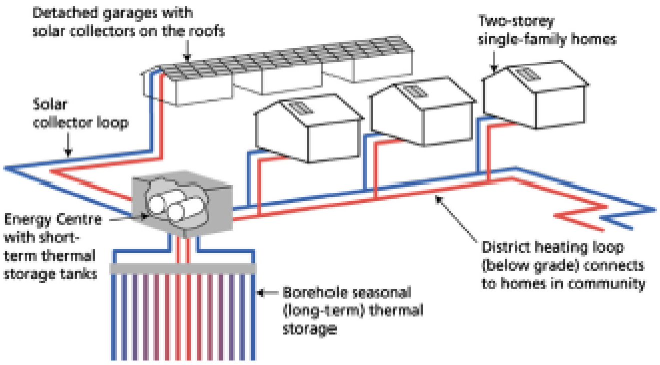

Figure 18 Borehole seasonal thermal storage (DLSC, 2012).

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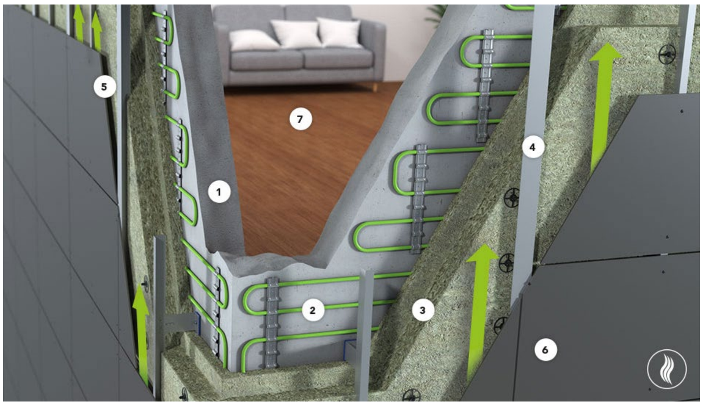
4 Building and Community

4.1 Energy active facades

The EU has committed to reducing its greenhouse gas (GHG) emissions by 55% by 2030 compared to 1990 levels. The building sector, responsible for 36% of GHG emissions, plays a crucial role in achieving these climate targets. Most notably, the existing building stock, which will still be 85-95% present in 2050, needs to be refurbished. Three-quarters of this stock are energy-inefficient and require comprehensive energy retrofitting and decarbonization over the next 20 years to enable climate neutrality. This will involve increasing the renovation rate to 3% and simultaneously transitioning to renewable heating/cooling systems.

Current standard renovations use External Thermal Insulation Composite Systems (ETICS), but their irreversible bonding to existing walls complicates material recycling and presents ecological disadvantages over their lifecycle. Long renovation times, including necessary scaffolding, pose significant barriers, affecting resident disruption and acceptance of the renovation process. Additionally, outdated energy distribution systems (heating distribution systems, radiators, etc.) pose risks due to leaks and demonstrate substantial improvement potential in terms of distribution losses and temperature levels. Modernizing heating distribution lines in existing buildings is often feasible only with significant construction efforts, thus incurring high costs and frequently necessitating resident relocation.

The ENERGY FACADE CEPA® was developed through collaborative research between SME Towern3000 and research institute AEE INTEC. It was conceptualized in a strategic sequence of preliminary projects. CEPA® represents both a radical and disruptive innovation in the energy retrofitting of existing buildings by combining the concepts of modular prefabricated facade elements and thermal component activation into a single approach.



1. Wall – Energy Storage (concrete, bricks…)
2. Heat emission system (heating/cooling)
3. Thermal insulation
4. Substructure
5. Ventilation
6. Facade cladding
7. Room

Figure 19: Exemplary system components of CEPA® energy facade, Source Towern3000

These large, highly insulated curtain façade elements can be manufactured in factories through standardized processes with high precision, reducing implementation errors in construction by 5-10%. The onsite assembly time for the approximately 20 m² facade module, using a mobile crane without scaffolding and involving about three personnel including HVAC components, can be reduced by up to 70%. One of the core elements is an active heat transfer layer, akin to a radiant heating system, integrated into the prefabricated facade element. By a patented concept, pressing the pipes or heat transfer surfaces onto the existing wall through the insulation in the facade module, the system's heat transfer capability significantly increases, roughly doubling the heat transfer performance and making the integration of heating layers in facade envelopes feasible.

By transferring heat from the outside, the thermal mass of the existing exterior walls is activated similarly to thermal component activation (TCA), facilitating load shifting and intelligent operation. The unlocked energy flexibility opens new markets and supports managing the increasing volatility in electricity markets driven by fluctuating renewable energies from solar or wind. In addition to monetary savings for portfolio managers or users, the "connectivity-market-friendly flexibility" plays a crucial role in the electrical economy by offering potentials for improved grid stability, grid security, and reduced investment needs in grid expansion. The ENERGY FACADE CEPA® addresses entirely new markets and customer groups.

The externally located TCA as a minimally invasive serial renovation concept with the potential for energy flexibility is seen as a game-changer. It aids property owners of large housing stocks not only in maintaining or increasing the value of their assets over the long term but also in integrating the three pillars of sustainability into their asset development strategies.

4.1.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

thermal energy storage

thermal comfort

electrical energy storage

4.1.2 Examples

Figure 20: CEPA heating/cooling layer installed on a multifamily house in Austria from Südsan-Project (left) and CEPA system installed in prefabricated façade element for serial renovation (right) source Towern3000

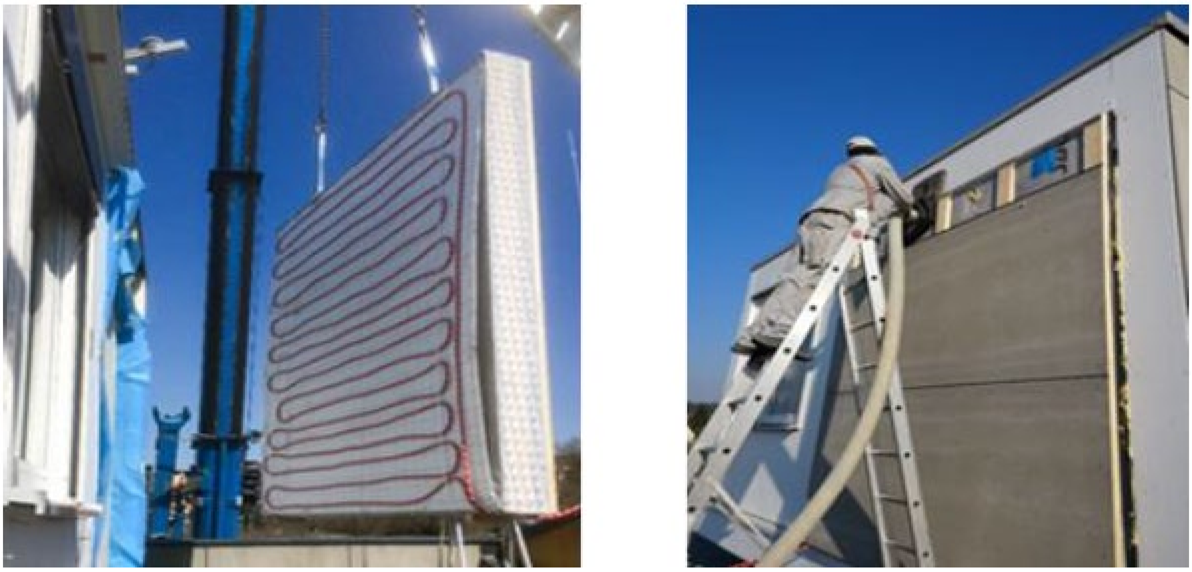


Figure 21: Velcro mounted heat dissipation system for building mass activation retrofit (left) and mounting of the prototype on the facade energy test rig at the laboratory of AEE INTEC (right), source AEE INTEC.

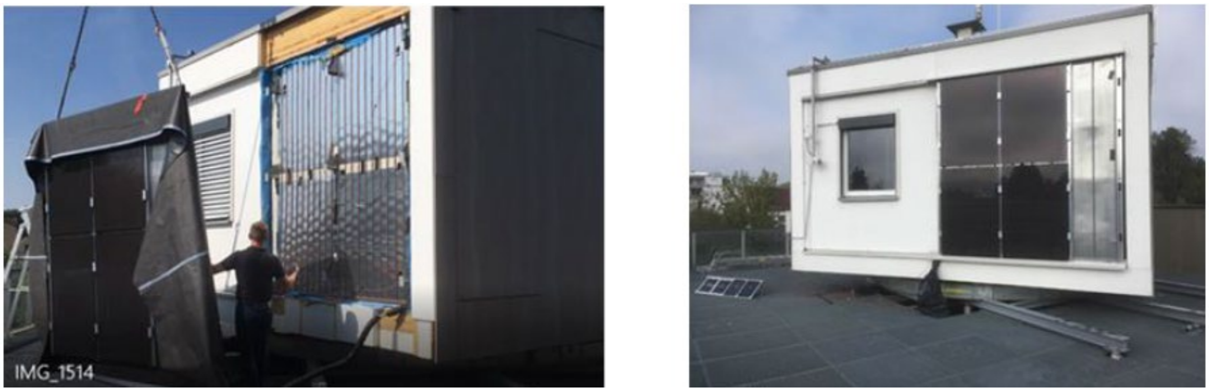


Figure 22: Active PV and heat dissipation layers of a multifunctional façade from EXCESS-Project (left) and the mounted prototype on the facade energy test rig at the laboratory of AEE INTEC (right), source AEE INTEC

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CEPA: https://www.cepa-solutions.com/

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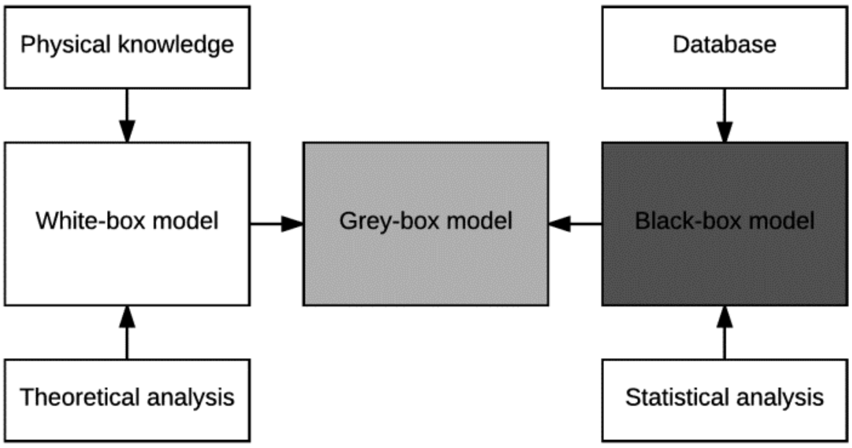
4.2 Digital Building Twins

The term digital building twin refers to a digital copy of a building and/or the associated building technology. Although digital twins are already being used successfully in practice in other industrial sectors, applications in the construction and real estate industry have so far primarily been investigated as part of research and demonstration projects. Digital twins can be used over the entire life cycle of a building.

The spectrum ranges from topics such as energy management at building and district level to optimizing construction site logistics and increasing the quality of use and efficiency of operation of buildings using model- or data based services. There are several types of digital twin that have been used so far. Some of them are:

- A three-dimensional geometric representation of the building structure and semantic information about building materials and components. Both elements - the 3D representation and the semantic attributes - form the basis of a building's Building Information Model (BIM).
- Information relevant to operation, such as commissioning and maintenance logs, warranty contracts, time series data from sensors and actuators recorded from building automation, IoT systems and weather services, transmitted to the building twin and used for monitoring, surveillance or optimization purposes. The aim of such a building twin is usually to optimize the control of the building technology or to do automated fault detection.
- There are different types of models, e.g. physical models for dynamic building simulation to assess the indoor climate and energy consumption which have mostly been used in the planning phase (white-box models), but also data-based artificial intelligence (AI) models from the field of machine learning (black-box models), which can be used for fault detection and diagnosis or the control of technical building systems in the operating phase. There are also grey-box model which combine physics-based information with real-time data from the building.

The digital building twin is therefore the virtual representation of a real building and its building services. By integrating sensors or other data sources, information on relevant parameters is continuously collected. This data are compared with the digital building twin in real time in order to visualize the current state of the building and identify possible optimization potential. Depending on the use case of a digital twin, there are different functionalities.



from: Yang Z. et al, 2017

Fault detection and diagnosis

During the life cycle of buildings, deficits such as fouling on the heat exchanger, failures of system components or defects in the sensors occur. Such deficits can be detected, diagnosed and rectified at an early stage with the help of a digital twin. Expert systems or data-based AI models can be used for this purpose. In the event of control violations or deviations from model predictions, the system generates a message with information about the fault and transmits it to the building operator via a suitable user interface. This will reduce maintenance costs.

Smart control and energy management

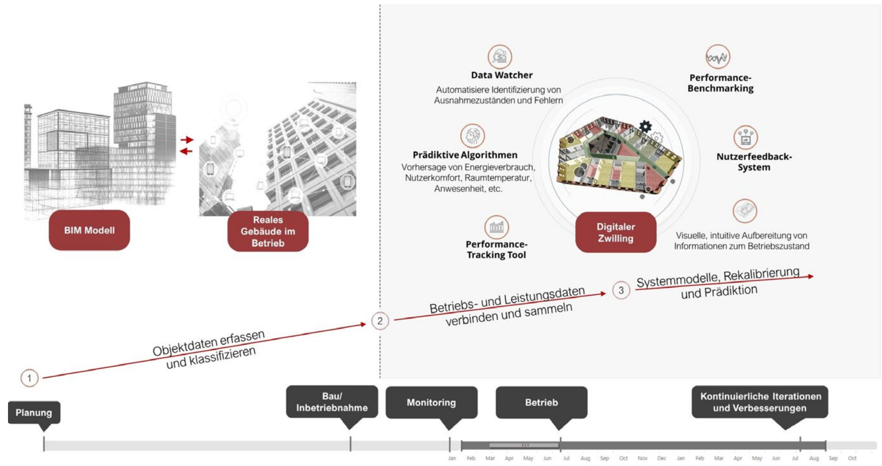
By analyzing historical and current data, a digital twin can make predictions about energy consumption and building performance. This allows the smart optimization of heating, cooling, lighting and other systems. One example of such applications can be found in the AI4HP1 research project, in which AI learns a digital building model from data in order to optimally control the heat pump.

4.2.1 Contribution to Solar Energy Buildings

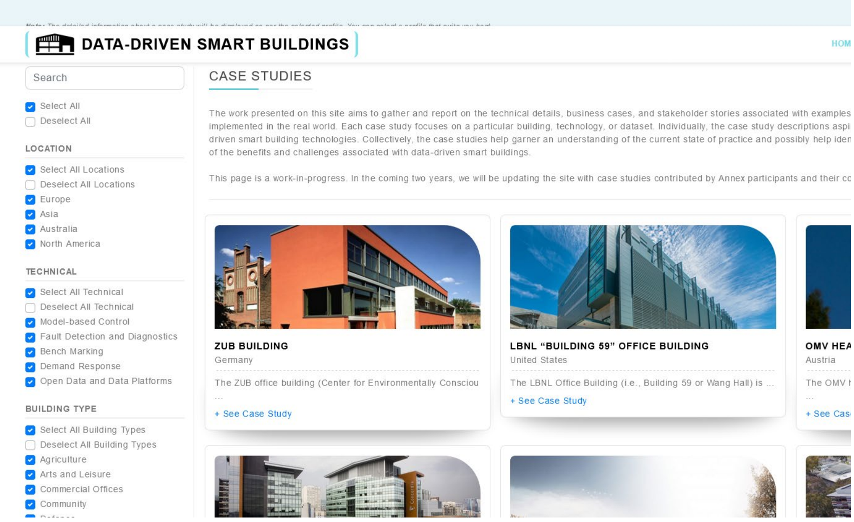
- primary contribution
- secondary contribution

- renewable energy generation
- building construction/renovation
- heating and or cooling
- energy self-resilience
- thermal energy storage
- thermal grid capacity
- electrical energy storage
- electrical grid stability
- thermal comfort

4.2.2 Examples



The BIM - based building operation platform - buildingtwin.at offers detailed insights into real-time building performance throughout the entire life cycle of real estate. Source: Buildingtwin.at)



DATA-DRIVEN SMART BUILDINGS

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BUILDING TYPE

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CASE STUDIES

The work presented on this site aims to gather and report on the technical details, business cases, and stakeholder stories associated with examples implemented in the real world. Each case study focuses on a particular building, technology, or dataset. Individually, the case study descriptions aspi driven smart building technologies. Collectively, the case studies help garner an understanding of the current state of practice and possibly help iden of the benefits and challenges associated with data-driven smart buildings.

This page is a work-in-progress. In the coming two years, we will be updating the site with case studies contributed by Annex participants and their co

ZUB BUILDING
Germany
The ZUB office building (Center for Environmentally Consciou …
+ See Case Study

LBNL "BUILDING 59" OFFICE BUILDING
United States
The LBNL Office Building (i.e., Building 59 or Wang Hall) is …
+ See Case Study

OMV HEA
Austria
The OMV …
+ See Cas

IEA EBC Annex 81 website offers a discription of case studies of data-driven smart buildings including applications of digital twins

(https://datasmartbuildings.org/)

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https://buildingtwin.net/

https://datasmartbuildings.org/

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4.3 Façade-integrated mini-split heat pump for decentral domestic hot water preparation

For a broad and fast phase-out of fossil-based decentral boilers and replacement of inefficient electric boilers in renovated multi-family buildings, decentral heat pumps are required. These heat pumps must be cost-effective, efficient, compact, silent and allow a low degree of invasiveness in the flat. Façade-integrated heat pumps allow on one hand to boost through prefabrication the renovation process, thus guaranteeing the cost-effectiveness of the installation, while on the other hand accessibility for maintenance and a pleasant architectonic appearance are preserved (Dermentzis et al., 2018; Siegele et al., 2019). Such heat pumps can be an alternative in this case for the flat-wise domestic hot water preparation but require typically a much deeper investigation of the airflow conditions through the façade-integrated element and a holistic development approach, as described in (Ochs et al., 2022).

Figure depicts a conceptual scheme of a developed R290 façade-integrated mini-split heat pump highlighted in (Monteleone et al., 2024). In this case, the heat pump outdoor unit, housing the evaporator and four axial fans, is integrated within the insulation layer of the renovated façade. The remaining components of the refrigerant cycle (compressor, expansion valve and condenser) are housed instead in the indoor unit. The indoor unit design features also a hot water storage, a freshwater station and the necessary hydraulic components for the charging of the storage and for the delivery of the domestic hot water demand. The size of the storage can vary between 90 and 120 Liters. A simulation study in (Monteleone et al., 2024) shows however that a 90 Liters compact storage would be already sufficient for a small family with moderate hot water consumption.

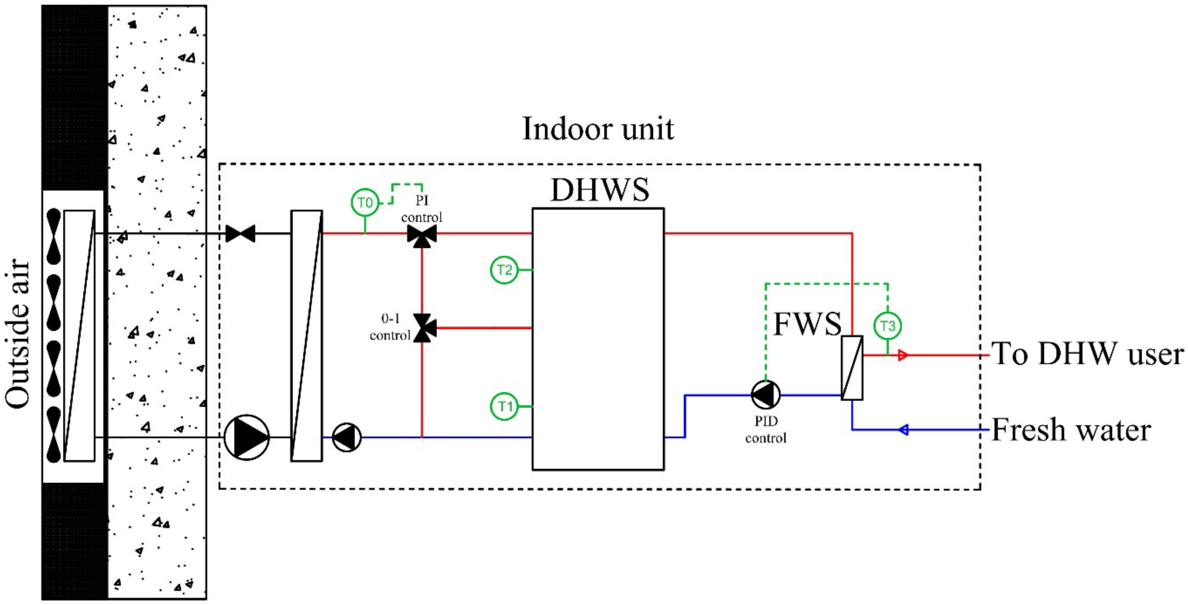

Figure 23: Conceptual scheme of mini-split façade-integrated heat pump for domestic hot water preparation. The scheme highlights the main refrigerant cycle and hydraulic components, as well as the domestic hot water storage (DHWS) and a freshwater station (FWS) (Source: University of Innsbruck; Monteleone et al., 2024)

During the startup phase of the heat pump, the top and bottom valve of the charging circuit are closed, and water is circulated in a loop. In this way, the inflow of cold water into the hot water storage is prevented. When the supply water temperature, measured by the sensor T0, is higher than 52 °C, the top part of the hot water storage is charged by means of fixed-value control so that comfort is guaranteed even for short term taps. As soon as the reserve volume is charged, the bottom valve opens, and the tank is charged via the intermediate layer. A hysteresis controller turns off the heat pump when the sensor T2 indicates a temperature equal to the setpoint plus 1 K and turns on again when the sensor T1 measures a temperature equal to 5 K lower than the setpoint. On the secondary side, the rotational speed of a PID-controlled inverter-based circulation pump is modulated to meet the comfort temperature requested by the user (sensor T3).

4.3.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

thermal comfort

4.3.2 Examples

Outdoor unit of the developed mini-split air-to-water heat pump with open casing. The evaporator as well as the four axial fans are shown in the foreground. Sound absorbing panels (in white) were employed on the outflow to minimize sound emissions. (Source: Monteleone et al., 2024)

(a) *(b)*

Illustration of the test façade with fully integrated heat pump outdoor element (casing below) and ventilation unit (casing above) installed in a PASSYS test cell at the University of Innsbruck (a); Functional model of the indoor unit inside the PASSYS test cell with indication of the main system components. A 200-Liters storage was used during the tests (b). (Source: University of Innsbruck; Monteleone et al., 2024)

4.3.3 References

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4.4 Model Predictive Control

Model Predictive Control (MPC) is an advanced control strategy that enhances energy efficiency in buildings, especially when integrated into Heating, Ventilation, and Air Conditioning (HVAC) systems. It offers significant benefits for the operation of buildings and energy communities and is particularly effective in balancing the trade-off between user comfort and energy consumption. The use of MPC in building energy systems, especially when coupled with renewable energy sources, is also highlighted as a key factor in reducing CO2 emissions and energy costs. The application of MPC in Solar Energy Buildings has shown to be advantageous in achieving energy-efficient building operation and can also achieve side targets like the reduction of peak demands.

How Model Predictive Control Works

MPC uses a mathematical model of the building's thermal dynamics to predict future states based on current conditions and control inputs. This control-oriented model includes the thermal characteristics of the building, HVAC system dynamics, and is bound by external factors such as weather conditions and occupancy patterns. The core of MPC is its prediction horizon, typically ranging from minutes to hours. During this horizon, the controller predicts the future behaviour of the building's temperature and energy consumption. It evaluates different control strategies to meet desired setpoints, such as maintaining comfort levels while minimizing energy use. At each time step, MPC solves an optimization problem that balances energy efficiency, comfort requirements, and operational constraints. Once the optimal control strategy is determined, MPC implements the first set of control actions, such as adjusting HVAC setpoints, switching energy sources or even operating individual components like valves and pumps. This process is also depicted in Figure 1 and repeats at the next time step, continually updating predictions and optimizing control actions.

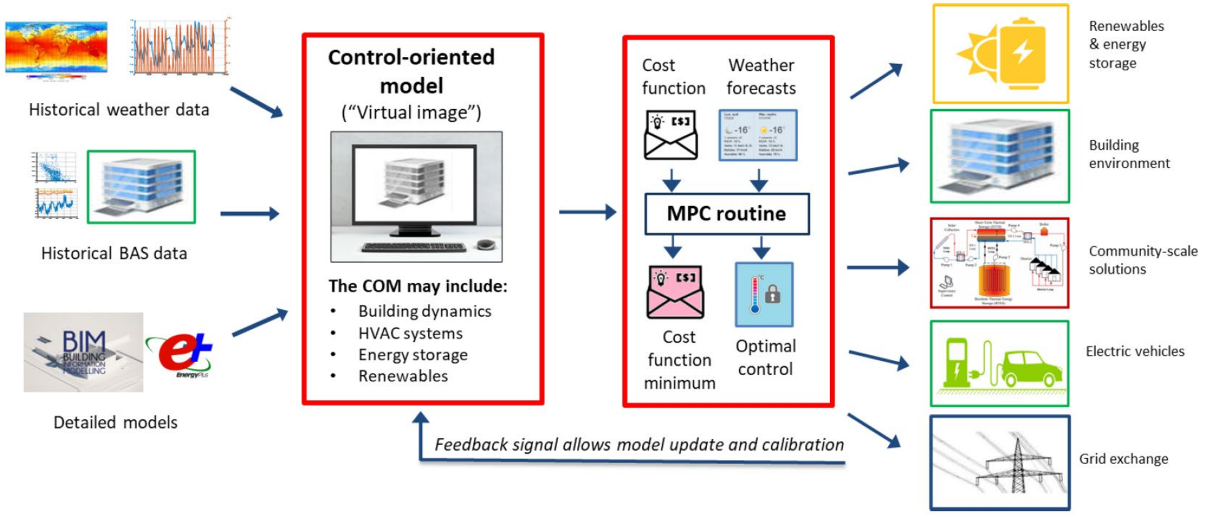

Figure 24: Concept of Model-Based Predictive Control in building energy management. (David Blum et al. 2023)

The implementation of MPC into HVAC systems involves several key steps:

- System Modeling: Develop a detailed mathematical model of the building and HVAC system. This can be done using tools like MATLAB/Simulink, Gekko, Pyomo or specialized software for building energy simulation.
- Real-Time Data Integration: Integrate sensors and smart meters to provide real-time data on indoor temperatures, humidity, occupancy, and energy consumption. Use forecasts to predict external conditions like weather, plug loads or hot water usage.
- Optimization Algorithm: Implement an optimization algorithm, typically a quadratic programming (QP) or linear programming (LP) solver, depending on the model complexity and requirements. The algorithm needs to be efficient enough to run in real-time, considering the computational resources available.
- Control Interface: Develop a control interface to apply the optimized control actions to the HVAC system. This may involve adjusting setpoints for thermostats, controlling chillers, boilers, and fans, and modulating dampers and valves for air and water distribution.
- Feedback Loop: Implement a feedback loop where the system continuously monitors the actual performance and adjusts predictions and control actions accordingly. Use historical data and machine learning techniques to refine the model over time and improve prediction accuracy.

In summary, Model Predictive Control provides a sophisticated approach to managing buildings and HVAC systems in energy-efficient buildings especially for weather dependent systems like Solar Energy Buildings. By leveraging predictive modelling, real-time data, and optimization techniques, MPC can help to achieve optimal performance with respect to various objectives like energy use, indoor comfort or CO_2-emissions.

4.4.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

heating and or cooling

thermal energy storage

electrical energy storage

thermal comfort

energy self-resilience

thermal grid capacity

electrical grid stability

4.4.2 Examples

LBNL Office Building

(Picture Source: Ruyssevelt et al., 2022)

The LBNL Office Building is a medium-sized office building located inside the Lawrence Berkeley National Laboratory (Berkeley Lab) campus in Berkeley, California. The building has 10,400 m^2 of conditioned spaces on four floors. The building was built in 2015 and retrofitted in 2019 to improve its energy efficiency. Model Predictive Control (MPC) technology was implemented in the BAS to optimize HVAC operations (supply air temperature setpoint, air damper position, fan speed, hot water valve position) for saving energy. For more information, see Ruyssevelt et al., 2022

Energetikum Office Building

(Picture Source: FH Burgenland)

Demo Energetikum is a living-lab office building located at the FH Burgenland campus in Pinkafeld, Austria. In this building, a data-driven predictive control of the HVAC systems is developed and tested. This control strategy is based on a grey-box modeling approach and data-driven parameter identification to predict the building's thermal behavior and calculate optimal control trajectories for the systems in place. The integrated systems include a reversible heat pump, thermal storage tank, thermo-active building systems, PV-plant and active shading of the glass façade. For more information, see Klanatsky et al., 2023 or https://prelude-project.eu/.

Sol4City Residential Building

(Picture Source: Gumhalter et al., 2023)

A simulation study in the research project Sol4City investigates the electrical grid interactions of a multi-family house designed for optimal solar energy coverage. The research employs dynamic building simulations, focusing on a reference building in Graz, Austria. Results show that Photovoltaic Thermal (PVT) systems together with thermal activation of building mass and MPC can maintain living comfort while reaching high solar fractions and mitigating electric peak loads simultaneously.
For more information, see Gumhalter et al., 2024

For more examples, see
https://datasmartbuildings.org

4.4.3 References

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Sol4City Project: https://nachhaltigwirtschaften.at/de/sdz/projekte/sol4city.php

Prelude Project: https://prelude-project.eu/

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4.5 Thermal Activated Building Systems

Thermal component activation has a long tradition. The first reports of heating and cooling ceiling systems appear as early as 1938, but these soon disappeared again due to inadequate thermal insulation standards and the poor control technology and system design of the time. At the beginning of the new millennium, however, thermal component activation experienced a resurgence, particularly in connection with cooling applications in office buildings. This development has continued, and thermal component activation has established itself as a surface heating and cooling system.

In recent years, additional tasks for component storage systems have provided new momentum. Specifically, thermally activated building components have been discovered as storage systems for fluctuating renewable energies (solar thermal energy, photovoltaic-heat pump, or wind power-heat pump combinations, etc.) and waste heat. The storage potential offered by thermal component activation can thus be used as flexibility options to increase renewable supply levels as well as for more efficient use through load shifting of higher-level infrastructures (heat and electricity grids, central generation capacities, etc.).

Simulation studies and field measurements show that the use of building component activation can significantly reduce the volume of water storage tanks that would otherwise be used (cost reduction, increased efficiency) and can also significantly increase the supply level of renewable energy sources through synergetic use and improved energy efficiency (low supply temperatures). Building component activation is already being used successfully in some single and multi-family homes, offices, school buildings, event, warehouse, production buildings, etc., from the point of view of increased energy flexibility in conjunction with renewable energy sources.

Regarding the influence of building component activation on the heating and cooling loads of buildings, there are already a number of pilot projects that have been implemented which highlight the advantages in terms of the dimensioning of the generation systems.

The basis for the function of component activation is the heat storage capacity of buildings, which is largely dependent on the material used. In most cases, solid concrete parts (foundation slabs or suspended ceilings) are thermally activated. In this way, structurally necessary components can be used simultaneously for heating or cooling the building. In addition, the good thermal conductivity of concrete ensures that the heat can penetrate quickly from the pipe register into the building component. Concrete also has a high heat storage capacity, which means that large amounts of heat can be introduced within a relatively short time without the component temperature changing significantly. However, other materials are also being thermally activated in pilot projects. For example, there are efforts and pilot projects with activated brick (new construction and renovation).

Figure: Installed TABS system before pouring concrete. The pipes for component activation are usually installed on the first reinforcement level of foundation slabs or suspended ceilings. Picture source: AEE INTEC

The Austrian timber construction company Thoma, which deals with the activation of solid timber components, takes a completely different approach in this respect. Although wood has only around 1/5 the density of concrete, it has twice the heat storage capacity. The disadvantage is its poor thermal conductivity. However, timber construction pioneer Erwin Thoma argues that wood is a very good heat accumulator and, together with component activation pioneer Harald Kuster, has already implemented several pilot projects with activated solid wood ceilings.

Different materials are used as pipe material in the activated components. In most cases, plastic pipes are used. The selection ranges from simple PE-RT pipes (non-cross-linked polyethylene) to cross-linked PEX pipes and plastic composite pipes with aluminium foil. The most important factor in selecting the right type of pipe is its long-term temperature resistance. While the operating temperature of PE-RT pipes should always be below 60 °C, PEX pipes are stable over the long term even at higher temperatures. Plastic multilayer pipes with aluminium foil have additional advantages in terms of high temperature and pressure resistance, dimensional stability, and oxygen tightness. In isolated cases, copper or aluminium pipes are also used. In principle, component activation can be viewed and operated like a very slow underfloor heating system. To utilize the full heat storage capacity of component activation, controlling the component and room temperatures plays a key role. Heat storage only works if certain temperature fluctuations (referred to as a "temperature band" in expert circles) are permitted. The width of the temperature band is small due to the requirements for thermal comfort and limited due to the high thermal inertia of building component activation or the fluctuations are very slow and constant. Temperature control in the building is possible in different ways. In practice, room and core temperature have emerged as the most important variables for efficient storage management.

4.5.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

thermal energy storage

thermal comfort

electrical energy storage

4.5.2 Examples

Use Case 1: The lower storey (foundation slab, intermediate ceiling) was built entirely in concrete, the upper storey is a lightweight timber construction. The building component activation was integrated directly (without a heat exchanger) into the solar primary circuit. Solar medium flows directly through the copper pipes in the component activation.

Spec. Heat demand:	22 kWh/m^{2}a
Gross area:	217 m^2
Gross collector area:	16 m^2 flat plate collectors
Energy storage:	1 m^3 water tank, 55 m^3 activated building mass
Auxiliary heating:	Water-operated living room stove
Solar fraction:	77 % (measured)

Figure 25: South view of a solar house in Tyrol (picture source: Building Owner)

Use Case 2: The heat and cold distribution of the Liefering sports hall in the city of Salzburg is primarily achieved with component activation. The component activation is hydraulically integrated into the system in the same way as underfloor heating. The high thermal inertia of the component activation allows a very small dimensioned auxiliary heating in relation to the heating load. The building is cooled via freecooling using the heat pump's extraction well.

Gross floor area:	4.610 m^2
Utilisation:	Municipal gymnasium, space heating, DHW
Use of surplus heat:	Tennis club in the neighboorhood
Gross collector area:	350 m^2 flat plate collectors
Storage Volume:	15 m^3 water storage, 1.500 m^3 activated building mass
Heat load:	383 kW
Auxiliary heating:	56 kW water/water-heat pump 15 kW immersion heater
Solar fraction	55 % (measured)

Figure 26: View of sports hall Liefering, Salzburg (picture source: AEE INTEC)

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4.6 Thermo-regulative nanofluid façade

Since the beginning of humanity, living species have used biological matters to separate and protect the environment from adverse effects. The skin is the main organ of natural protection and regulation, capable of defending against impacts, temperature variations, radiation, micro-organisms, and chemical products. The use of clothing and the construction of buildings are essential activities for human survival and existence. The alligators (Figure) in the morning stay out of the water, taking advantage of the sun to increase their body temperature, curiously with their mouths open for greater contact with the sun's rays. In the afternoon - they are out of the water because the temperature outside is higher. The thermo-regulative façade is motivated by the challenge of providing a comfortable interior space while the outside temperature fluctuates and is based on a biomimetic element "inspired by nature".

Figure 27: Thermo-regulative in nature (Moraes 2019).

The concept consists of an advanced technological wall façade, integrating a volumetric solar absorption water-based fluid with nanoparticles to increase thermal capacity and comfort of the buildings. The façade is composed by 2 cavities with a thermal insulation in the middle. During summer, cold water is embedded in the inner cavity during the day and transferred to outer cavity during the night (Figure). During winter, the opposite process is taking place (Figure). To enable this dynamic behaviour two small pumps and control is required. Insulated water walls are ideal for two reasons: water has over twice the heat capacity of concrete by volume and heat flow through water is more rapid since fluid can transfer heat by internal convection currents. The concept is adapted by the work of Antonia Kalatha in 2016, a concept of water wall originates from research done on the field of biomimetics and inspiration gained from living organisms maintaining their body's temperature within comfort limits.

In the present concept the water is replaced by nanofluid. The nanofluid absorbs volumetrically the solar radiation not depending on surface properties and avoiding thermal resistance. Nanofluids are advanced fluids having a colloidal solution of nano-sized particles of metallic in another fluid. Nanofluids are being used in solar energy systems as working fluids and as a storage medium in thermal storage systems. Experimental and numerical analysis done shown that addition of nanoparticle enhances the thermophysical and thermal transport properties of the working fluids such as the thermal conductivity.

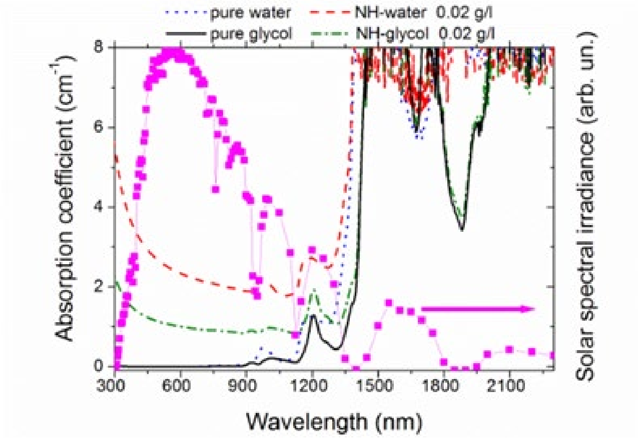


Figure 28: Spectral absorption coefficient of nanofluids and base fluids (Moradi et al. 2013).

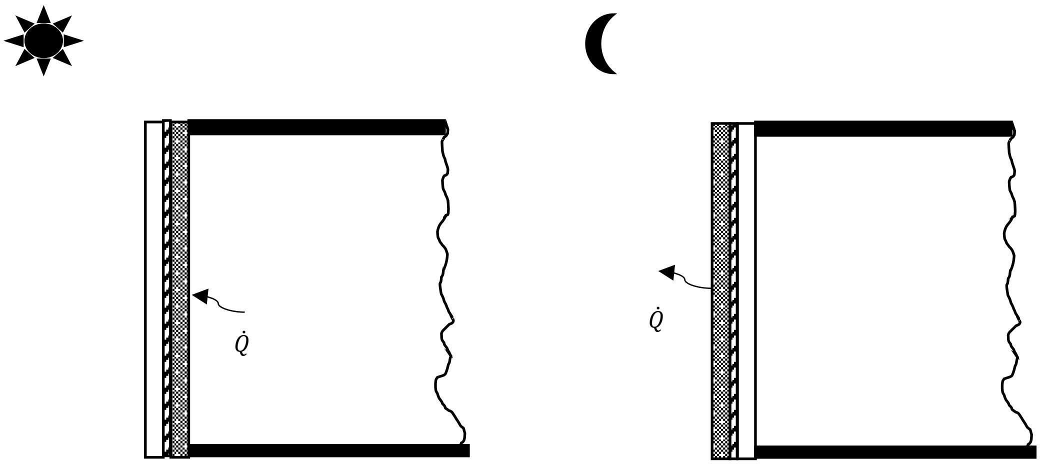


Figure 29: Summer (Facão 2024).

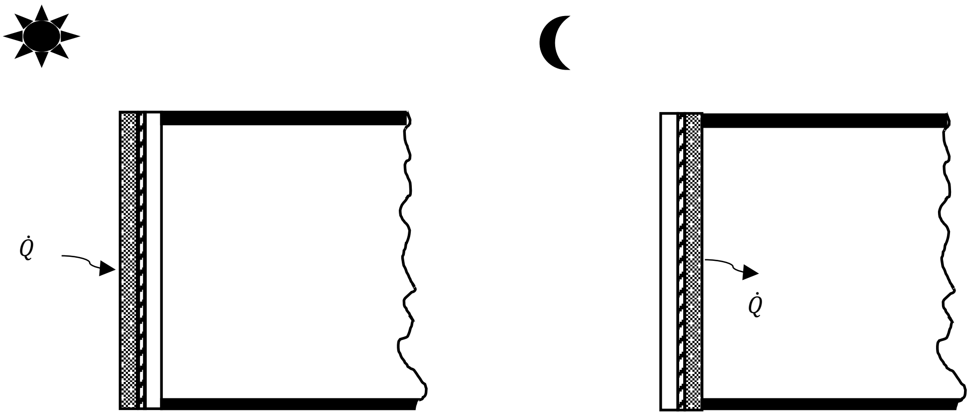


Figure 30: Winter (Facão 2024).

Two test cells were installed to test the presented concept. The test cells are: one reference cell with a masonry wall implemented in the south façade and one cell with a dynamic nanofluid wall (water with cooper nanoparticles) implemented in the south façade. The two models are made of two galvanized steel sheets lacquered with 0.50 mm thickness, and 40 mm of insulation in rigid polyurethane foam injected with density 40 kg/m^3. The south-facing masonry wall is composed by double wall with brick of 11 cm, 4 cm of XPS thermal insulation, plaster, and white painting.

Figure 31 presents the design of the nanofluid wall. The thermo-regulative behaviour of the fluid is done with two submersible pumps installed in the inner and the outer cavities. The wall is made in transparent acrylic sheets and with 50 mm of thermal insulation with agglomerated cork. The thickness of the fluid wall is 120 mm.

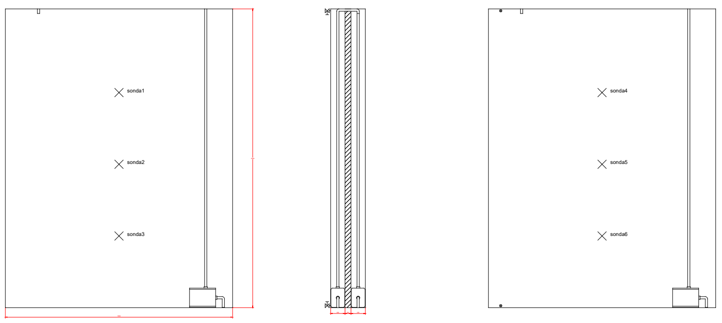


Figure 31: Nanofluid wall (Facão 2024).

4.6.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

thermal energy storage

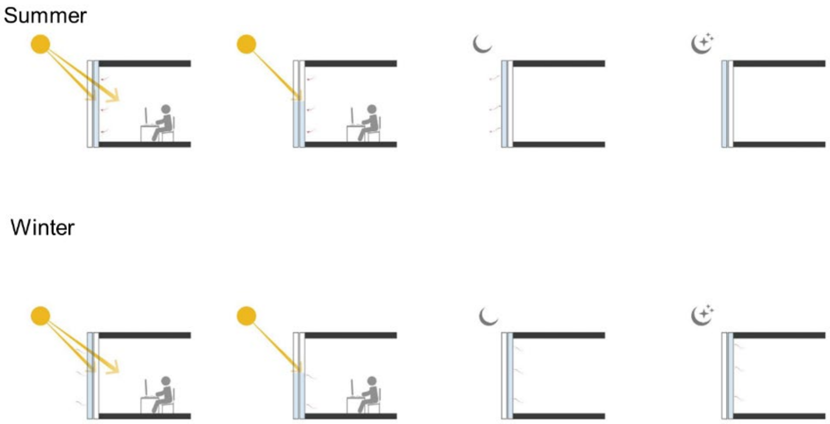
electrical energy storage

building construction/renovation

energy self-resilience

thermal comfort

4.6.2 Examples



Applying thermo-regulation to façade elements (Kalatha 2016).

Conventional masonry wall (left) and thermo-regulative wall (right) (Nunes 2021).

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5 Thermal Grid technologies

5.1 Absorption Heat Exchanger as Transfer Substation for District Heating

An optimized future district heating grid is designed to be supplied exclusively by renewable energy sources, including geothermal, industrial waste heat, and solar thermal energy. The primary circuit should operate at lower temperature levels compared to traditional systems, which enhances overall efficiency and sustainability. The key components and their functions in this optimized system can be realized by replacing the traditional heat exchanger (HX) at the transfer substation to an absorption heat exchanger (AHX) [1-3].

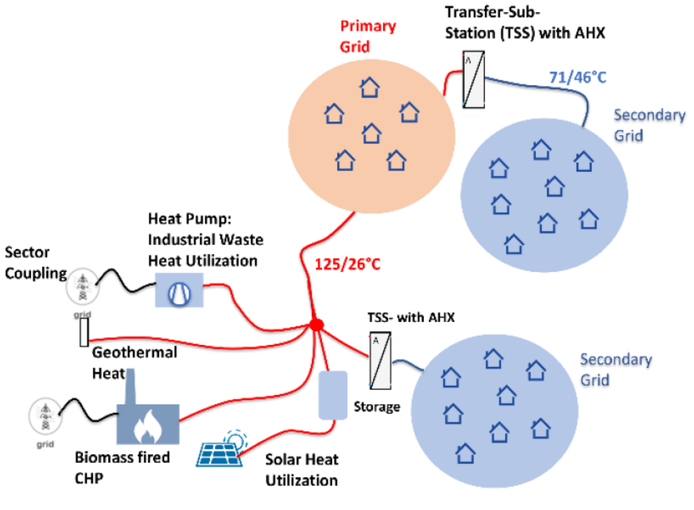

Figure 32: Schematic drawing of the optimized future district heating grid, where the primary circuit is operated at lower temperature levels by using absorption heat exchanger (AHX) instead of an HX as transfer-substation (TSS) (125/56°C at primary circuit and 71/46°C at secondary grid) [4] (Source: AEE INTEC)

Therefore, the Absorption Heat Exchanger (AHX) is used to actively reduce the return flow temperature in large heat transfer stations. It uses the higher flow temperature on the primary side to actively reduce the return temperature [5].

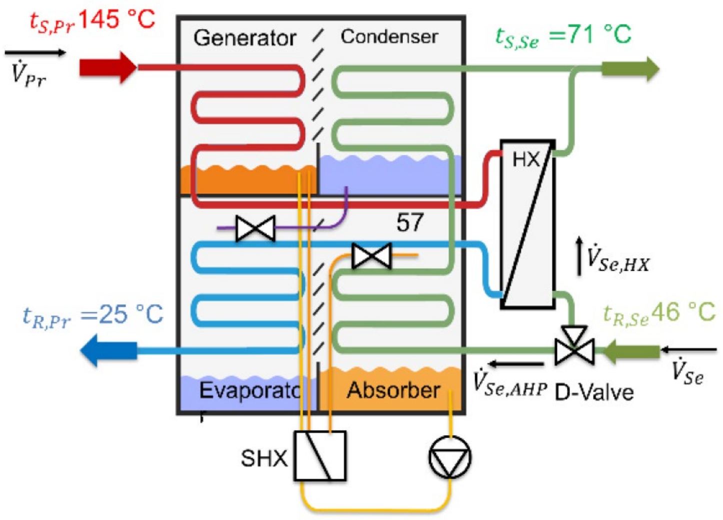

Figure 33: Principal picture of an absorption heat exchanger (AHX) consisting of an AHP and a HX and a distribution valve (D-valve) [6-7] (Source: StepsAhead)

The AHX is a combination of an absorption chiller with a heat exchanger (HX), as depicted in Figure 2. Unlike traditional chillers or heat pumps, the AHX functions as an exergetically optimized heat exchanger. In this configuration, the hot water circuit (external heat transfer fluid) is short-circuited with the cold-water circuit (external heat transfer fluid) of the absorption chiller via the heat exchanger, forming the primary circuit of the AHX. On the secondary side, the cooling water circuit (external heat transfer fluid) is split between the HX and the absorption chiller through a distribution valve (D-valve). [6-7]

The AHX leverages the exergetic potential from the large temperature difference between the two supply temperatures ($\Delta tS{,}Pr/Se$) to drive an absorption heat pump (AHP) for subcooling the temperature $tR{,}Pr$ below $tR{,}Se$ in the evaporator of the AHP. [7]

Designing an absorption heat exchanger (AHX) presents several challenges identified in the experimental and simulation-based results, that need to be addressed for optimal performance. They include [8]:

- **Subcooling performance**: Achieving high subcooling performance in an AHX requires a balance of a high primary supply temperature, a low secondary return temperature, and a high secondary-to-primary mass flow rate. Designing the system to handle these temperature differentials effectively is crucial for maximizing subcooling efficiency.
- **Optimizing Mass Flow Rates**: The partitioning of the secondary mass flow between the absorption chiller and the heat exchanger plays a significant role in the subcooling performance of the AHX. Balancing and optimizing mass flow rates from different components within the system is essential for achieving the desired subcooling levels.
- **System Efficiency**: Ensuring overall system efficiency while designing an AHX is vital. This includes considering factors like pressure losses, irreversibility in each heat exchanger, and temperature glides within the system. Maximizing efficiency while minimizing losses is a critical challenge in AHX design.
- **Integration in District Heating Grids**: Integrating an AHX into existing district heating grids faces challenges due to fixed pipe diameters and limitations on maximum mass flow rates. Overcoming these limitations without extensive infrastructure changes, such as installing larger pipes, requires innovative design solutions.
- **Temperature Spread and Heat Capacity Increase**: Designing an AHX to achieve a significant temperature spread between primary return and supply temperatures is essential for increasing the heat capacity of district heating grids. Ensuring that the AHX can effectively subcool the primary return temperature below the secondary one without compromising system efficiency is a key challenge.

Addressing these challenges through careful design considerations and optimization is crucial to harnessing the full potential of absorption heat exchangers in district heating applications.

A pilot-scale Absorption Heat Exchanger (AHX) was developed and tested. The AHX combines a single-stage absorption chiller (H2O-LiBr) with a nominal cooling capacity of 15 kW and a counterflow plate heat exchanger (HX) with an area of 2.46 m². The experimental setup was integrated into the lab and equipped with the necessary measurement tools to analyze its performance under various operating conditions. Firs experimental results show that the heat capacity within existing grids can be increased up to 30% with unchanged flow and temperature inlet conditions and more renewables can be integrated easily. The highest subcooling at 20 K can be reached at pilot-scale at high primary supply temperatures of about 145°C at lower primary supply temperatures at about 125°C subcooling resulted in 12,5 K. [4-6]

As a follow up, an AHX model (using the same working pair) has been implemented in Modelica and validated on those experimental results. The model is upscaled up to a 2.8 MW absorption heat exchanger to match the size of the concerning substation. The dynamic simulations showed a reduction of the return temperature at the primary side of the whole year, and it is estimated to be in the range of 7 to 25 K. This means, a reduction of the mass flow rate at the primary side of a yearly average of about 22%, or the grid could be extended of about 22% without the need of any change on the primary side piping. These results underlined the theoretical considerations that can be used by the AHX. All in all, a large difference between the supply temperature of the primary and secondary circuit is required to subcool the return temperature at its highest value. This condition applies to DH grids of future generations with associated sub-networks. [7]

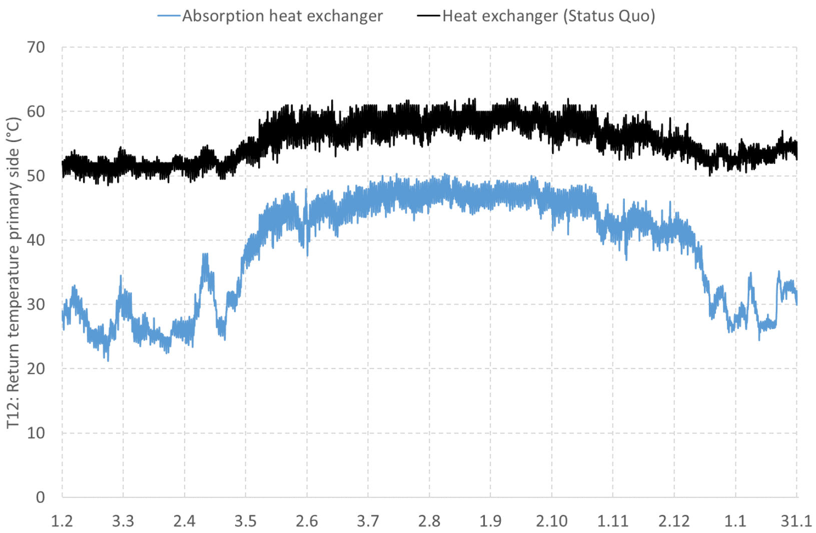

Figure 34: Principal system results of the AHX model in Modelica (comparison between transfer substation with standard heat exchanger to transfer substation with an absorption heat exchanger) (Source: AEE INTEC)

5.1.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

building construction/renovation

heating and or cooling

energy self-resilience

thermal energy storage

thermal comfort

5.1.2 Examples

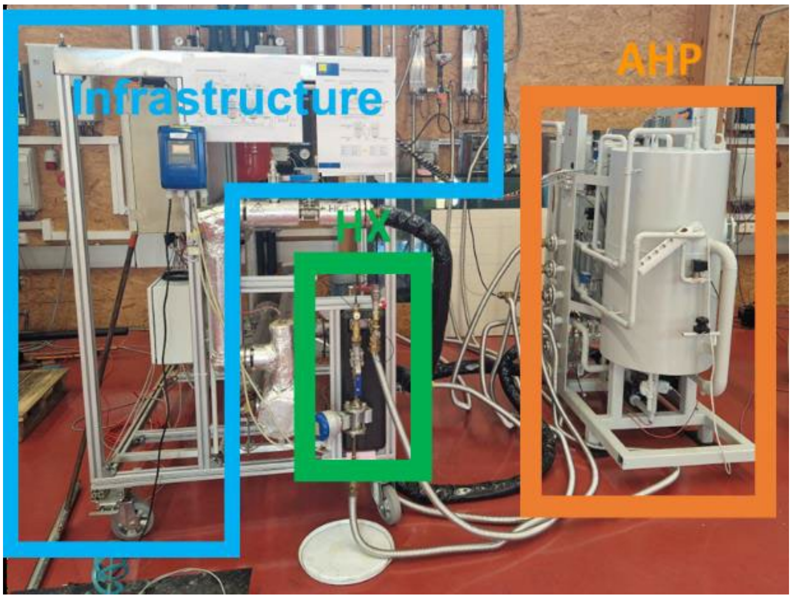

Figure 35: Picture of the AHX test bench at AEE INTEC, consist of an AHP (in orange) and a HX (in green) integrated in the infrastructure of the laboratory [6] (Source: AEE INTEC)

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5.2 Anergy or ultra-low temperature networks

In cold district heating systems, as the name might suggest, the temperatures of the heat transfer medium in the grid is comparatively low ranging from approximately 5-30°C over the course of the year. With supply temperatures of <30°C, cold district heating networks can a) utilise low-energy heat sources such as waste heat or renewables, b) almost completely eliminate transport losses, c) achieve significant primary energy savings compared to the state of the art and d) provide both heating and cooling with the same infrastructure. Innovative network topologies allow a high degree of flexibility in terms of supplying existing and new buildings as well as expanding and integrating new sources, sinks and storage systems. To utilise the energy from the cold grid and provide temperatures at the appropriate demand level, heat pumps must be installed at the final consumer centres/stations.

Figure shows a possible system concept for a cold district heating network. It shows different heat production, consumption and storage units and their mode of operation in the network.

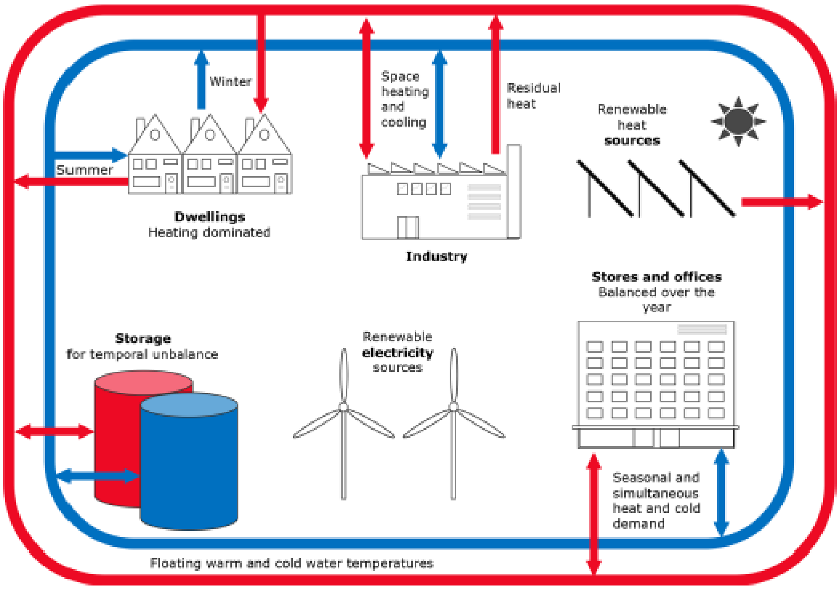

Figure 36: Concept scheme of a cold district heating system with different source, sink and storage units. [Boesten et.al., 2019]

A key difference to conventional heating networks is that cold district heating systems are operated on a decentralised basis. This means that there is no centralised, demand-controlled firing or heating system, but rather many decentralised feeders and consumers, which can be operated in different ways depending on the demand. Furthermore, there is no predetermined flow direction in the network. The network, consisting of a hot and a cold pipe, can therefore be operated bidirectionally. [Buffa et.al., 2019] researched the different system concepts extensively and gave a comprehensive overview of possible layouts and classification of those. In [Leppin, 2022], systems of different sizes and topologies were analysed and evaluated based on various criteria (economic, technical, ecological). Deterministic and stochastic approaches were used.

5.2.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

thermal energy storage

electrical energy storage

building construction/renovation

energy self-resilience

thermal comfort

5.2.2 Examples

FGZ Zürich CH

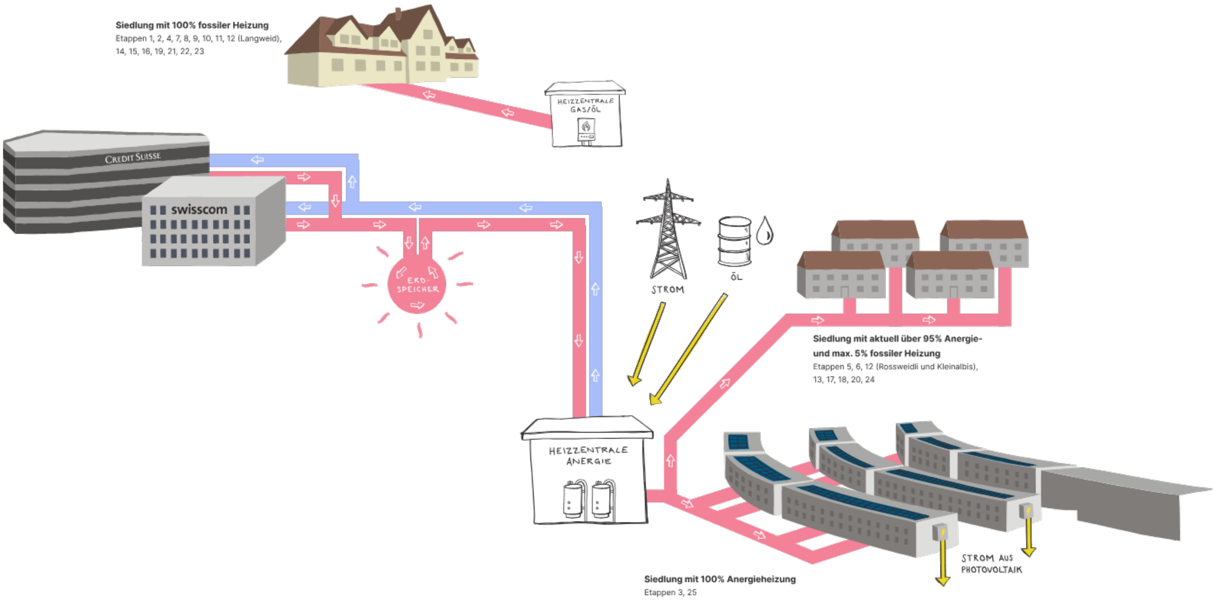

Figure 37: Cold district heating grid of the "Familienheimgenossenschaft Zürich", using waste heat from two big data centers in combination with seasonal geothermal storages. [Source: https://fgzzh.ch/warme-und-energie/]

Garten der Generation, Herzogenburg AT

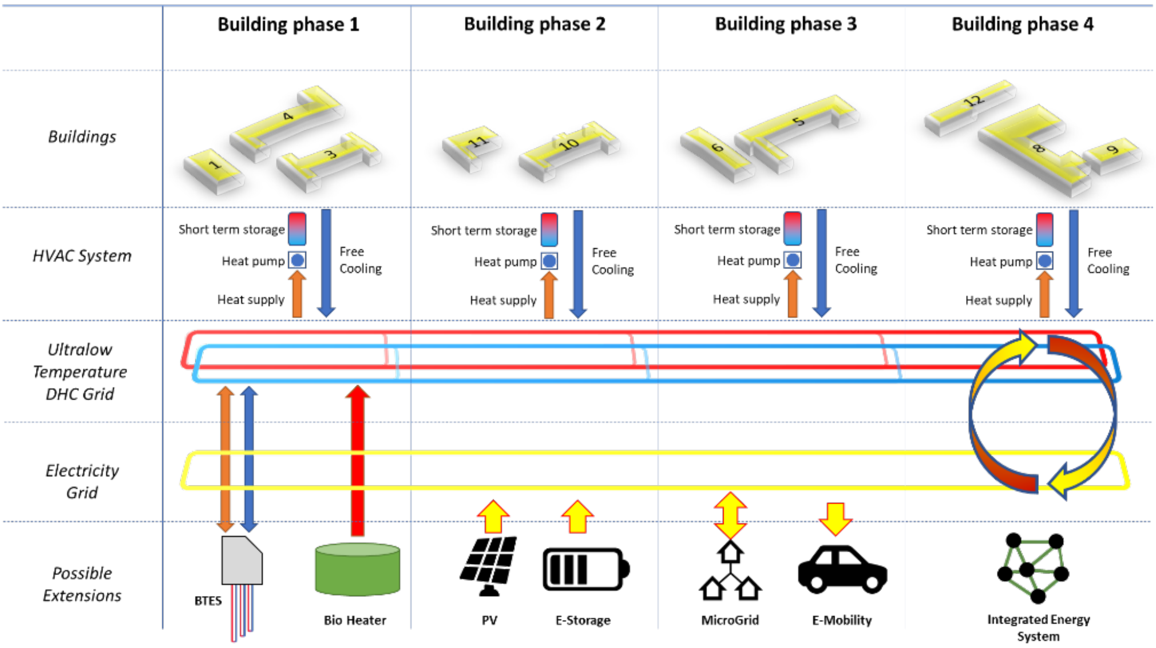

Figure 38: System schematic of the cold district heating grid in the "Garten der Generationen" living quarter. The system will be extended in consecutive building phases, integrating multiple energy carriers and sources. [Source: AEE INTEC]

Figure 39: Concluded first building phase of the "Garten der Generationen" with solar thermal production units and a thermally utilizable pond as one part of multiple storage capacities in the system. [Source: Garten der Generationen e.V.]

Viertel2, Vienna AT

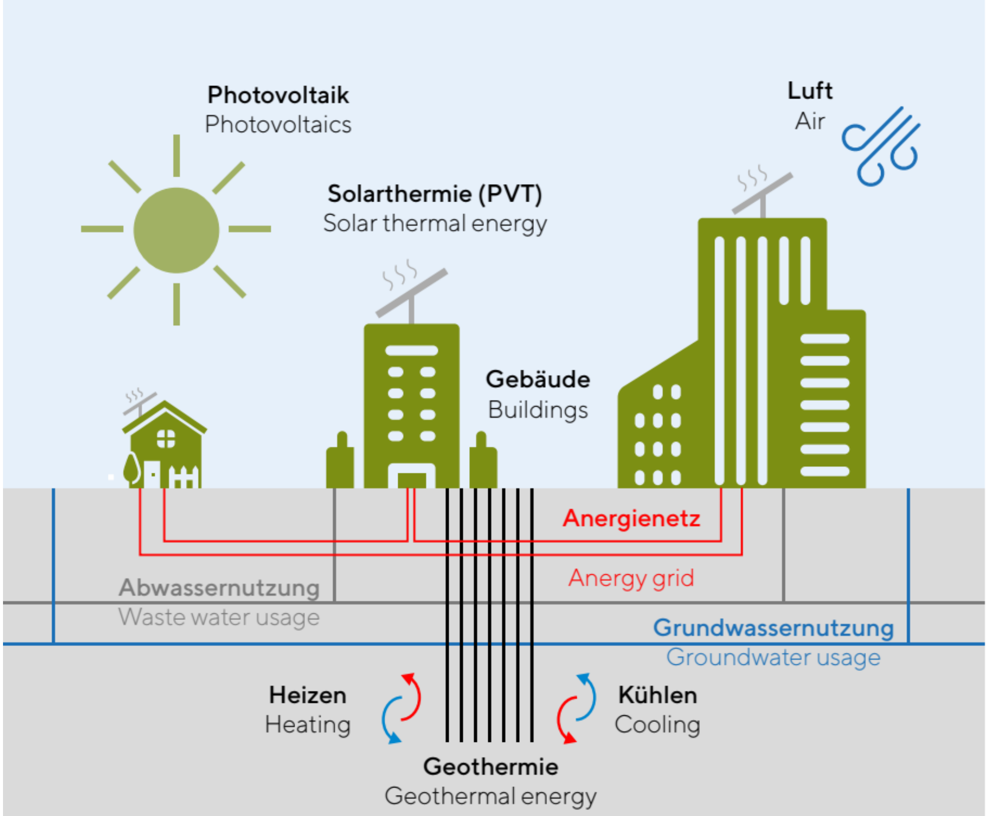

Figure 40: The Viertel2 system combines renewable energy sources such as geothermal energy, groundwater, wastewater, waste heat and photovoltaics to supply 479 flats, 350 student flats, 25,500 square metres of office space and, in future, two high-rise buildings and a school. [Source: https://www.viertel-zwei.at/wp-content/uploads/2021/09/Zweitung07_280x420_WEB_Doppel.pdf]

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5.3 Solar thermal district heating

Solar heating plants for district heating areas are often based on large solar collector fields mounted on the ground, see figure 1.

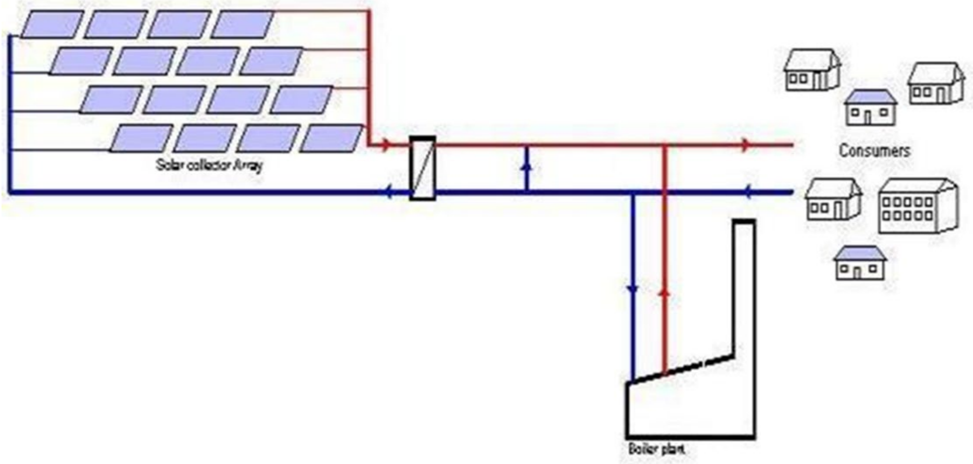

Figure 1. Schematically sketch of solar district heating system.

In most plants the collector field consists of a high number of parallel connected solar collector rows with up to 20 large collector panels in serial connection. In the morning of a sunny day a circulation pump is circulating the solar collector fluid through the solar collector loop to heat up the fluid and the pipes. When the solar collector fluid has reached a sufficiently high temperature, the fluid is directed through a flat plate heat exchanger, see figure 2. In this way solar heat is transferred to the water in the district heating network. During the sunny day the circulation pump is circulating the solar collector fluid through the solar collector field with a volume flow rate of about 0.2 l/min per m² collector area. Often the volume flow rate is controlled in such a way that the outlet temperature of the solar collector fluid from the collector field is maintained at a constant level during the day. Therefore the volume flow rate is variating through the day. In periods with a high solar irradiance on the collectors the volume flow rate is high and in less sunny periods the volume flow rate is low.

Figure 2. Flat plate heat exchanger. (DTU)

In most plants relatively simple flat plate solar collectors with one or two cover plates are used. Often two different collector types are applied. In the first part of the rows collectors with one cover plate are used and in the end of the rows solar collectors with two cover plates - often a glass cover and a polymer foil - are used. In this way the collector efficiency will be high both in the start of the rows where the solar collector fluid temperature is low and at the end of the rows where the solar collector fluid temperature is relative high. Further, the costs of the solar collector field will be relative low since simple and inexpensive collectors are used in the start of the rows.

In some plants concentrating tracking solar collectors are used. Both one axis tracking and two axis tracking collectors can be applied. Concentrating solar collectors have very low heat loss coefficients resulting in high efficiencies at high solar collector fluid temperatures. Therefore concentrating solar collectors are suitable for district heating networks with high temperature levels.

The solar heating plant can cover a small or a high part of the heat demand in the district heating area in question, depending on the heat demand, the collector area and the volumes of the heat storages in the system. Often district heating networks are equipped with steel hot water storages. These heat storages can be utilized by the solar collector fields and in this way an increased part of the heat demand in the towns can be covered by the solar collectors.

During the last 5 years many district heating systems have installed large heat pumps. These electrically driven heat pumps cool down the heat storages. The decreased temperature level of the heat storages will decrease the temperature level in the solar collectors and consequently increase the thermal performance of the solar collectors. Some solar heating plants have large seasonal heat storages, for instance water pit storages. These storages can further increase the solar fraction of the solar heating plants and also secure a good interplay with the energy system, because the heat storages can be used by different energy technologies, see figure 3. For instance, periods with low-cost electricity and low-cost heat can be used to charge the heat storage.

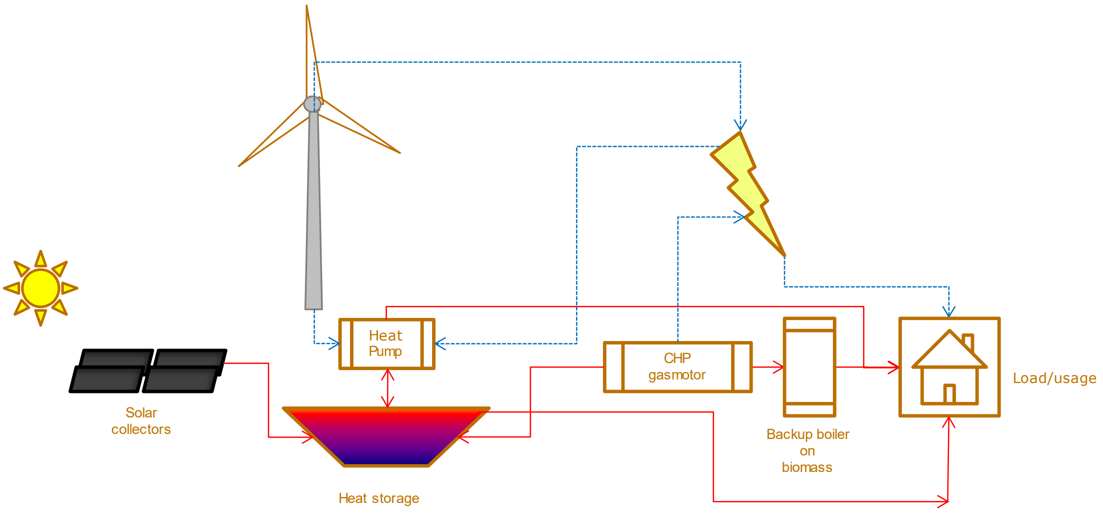

Figure 3. Combined technologies and smart heat storage interacting with the electric grid.

Solar heating plants for district heating are based on a reliable, durable, easy to install and relatively simple and inexpensive technology. Consequently, solar heating plants have typically high thermal performances, very low energy/CO_2 emission pay back times, low operational and maintenance costs and life times higher than 30 years. Typically the yearly efficiency of Danish solar heating plants is 40%, that is: 40% of the solar radiation reaching the surfaces of the solar collectors are utilized.

5.3.1 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

energy self-resilience

heating and or cooling

thermal comfort

thermal energy storage

5.3.2 Examples

The following examples are all from Denmark.

Large flat plate solar collectors under development/test at the Technical University of Denmark. (DTU)

Solar collector rows at Marstal solar heating plant. (DTU)

Solar collector field with a total collector aperture area of 156,694 m² at Silkeborg solar heating plant. (DTU)

Two axis tracking concentrating solar collectors at Lendemarke solar heating plant. (DTU)

Two axis tracking concentrating solar collectors at Hørsholm solar heating plant. (DTU)

One axis tracking concentrating solar collectors at Brønderslev solar heating plant. The plant is used for both district heating and electricity production.(DTU)

Flat plate collectors with one and two cover plates and one axis tracking concentrating solar collectors at Tårs solar heating plant. (DTU)

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5.4 Green district heating in existing district heating tubes

When it comes to energy transition, the focus extends beyond electricity generation to encompass the crucial domain of heat supply. In Germany, approximately 50 % of final energy consumption is attributed to heat usage. Within this context, the concept of green heat networks emerges as a pivotal player in the quest for sustainability. Especially the integration of green heat in already existing district heating systems will be crucial to achieve the goals in efficiency and decarbonization.

What Are Green Heat Networks?

Green heat networks, also known as district heating systems, are ecologically oriented infrastructures that distribute heat to residential and commercial areas. These networks operate by connecting multiple buildings to a central heat source, which can be powered by renewable energy or industrial waste heat. Here's how they contribute to the heat transition:

1. Reducing Carbon Emissions:
   By integrating heat from renewable sources (such as geothermal, solar thermal, and biomass) and industrial waste heat, green heat networks significantly lower CO_2 emissions compared to conventional fossil fuel-based systems.

2. Challenges and Opportunities:
   Transitioning to green heat networks involves overcoming existing limitations. Many current networks rely on fossil fuels like coal and gas, necessitating a shift toward lower-temperature heat sources. Retrofitting existing networks to accommodate renewable energy requires careful consideration of industrial heat demand and building conditions.

3. Technological Solutions:
   To achieve a sustainable balance, various technologies can be explored.
   - Abundant Geothermal Energy: Geothermal heat pumps tap into the Earth's natural warmth, but their feasibility depends on local geological conditions.
   - Solar Thermal Collectors: These require ample space for collector fields, which may compete with other land uses.
   - Large-Scale Heat Pumps: Efficient heat pumps can extract warmth from the environment, but their implementation must align with seasonal heat storage solutions.

Assessing Green Heat Networks Using GIS-Based Analysis

In the pursuit of sustainable urban development, evaluating green heat networks through Geographic Information System (GIS) analysis plays a crucial role. Here are some methods for assessing / evaluating green heat networks:

1. Urban Heat Island (UHI) Vulnerability Mapping:

   - UHI refers to localized temperature increases in urban areas due to factors like impervious surfaces and limited vegetation. GIS tools can model UHI vulnerability by integrating high-resolution spatial data, socio-demographic information, and customized indicators. These indicators may include heat exposure, population sensitivity, and adaptive capacity. By mapping UHI hotspots and identifying vulnerable areas, decision-makers can prioritize interventions and adaptation strategies.

2. Multi-Criteria Analysis for Urban Green Spaces:

   - Urban green spaces contribute to well-being and ecological balance.
   - GIS-based multi-criteria analysis helps select suitable sites for green spaces.
   - Criteria include ecological importance, socioeconomic factors, mental health benefits, and more.
   - By overlaying spatial data, decision-makers can identify optimal locations for green heat network installations.

3. Urban Heat Island Mitigation Strategies:

   - GIS analysis aids in identifying areas with intense UHI effects.
   - Factors like building density, land use, and green infrastructure influence UHI.
   - By assessing these factors spatially, planners can devise effective mitigation measures.
   - Potential solutions include integrating renewable energy sources, optimizing district heating layouts, and promoting green roofs and walls.

In summary, GIS-based evaluation provides valuable insights for designing and implementing sustainable green heat networks. Decision-makers can leverage these methods to enhance urban resilience and reduce carbon emissions. Striving for a climate-neutral future, green heat networks will play an increasingly vital role. Collaborative efforts among policymakers, energy providers, and urban planners are essential to expand these networks, reduce emissions, and ensure sustainable heat supply for our cities and communities.

5.4.1 Project Examples of green heat integration – MineATES

Introduction

To achieve sustainable heat generation in the building sector, a future utilization of renewable resources is required. Especially geothermal energy is a highly feasible option leveraging the carbon neutral heat supply of the future because it is one of the only base-load capable renewable heat sources. Furthermore, it has the advantage to perform a cyclic energy regeneration in times of a low heating demand. This advantage especially applies to the utilization of mine water. However, extracting much heat will likely cause the mine to cool down in the long term, resulting in a failure of the connected energy supply system. To counteract this, the idea in the MineATES project is increasing regeneration by feeding subsurface green (waste) heat and thus considered the former mining structures as a low-temperature aquifer heat store (ATES). This should be done with the help of heating networks to establish an innovative option of green district heating in suitable areas.

Spatial Analysis of local suitable renewable heat potentials and heating demands

The DBI Gas- und Umwelttechnik GmbH in Germany are experts in geospatial modelling for more than a decade. In many research projects, the basis for the current modelling was established. The DBI building atlas forms a geodatabase with address coordinates of each individual building in Germany. In the project MineATES the geodata will be enriched with location-specific parameters to calculate house-specific heating demands using geospatial analysis. Figure 1 shows an algorithmic scheme of the geospatial model which is executed in five steps:

1. Recording addresses with geo-coordinates and store in the geodatabase
2. allocation of building dimensions to each geodata set in various qualities
    I. heating surface from 3D building data (if available)
    II. heating surface from 2D-open-source building data
    → derive building height, number of floors, household size, number of households, etc.
3. assignment of specific heat demand parameters according to:
    I. building type
    II. building age
    III. age of heating system, etc.
4. Execution of the algorithm (Figure 1) to simulate the house exact heat demand
5. regionalization of the heat demand with additional characteristic values, such as:
    I. Regional climate data (grid-based geodata sets)
    II. Building refurbishment status and other official statistics, Socio-demographic parameters, e.g., age of residents

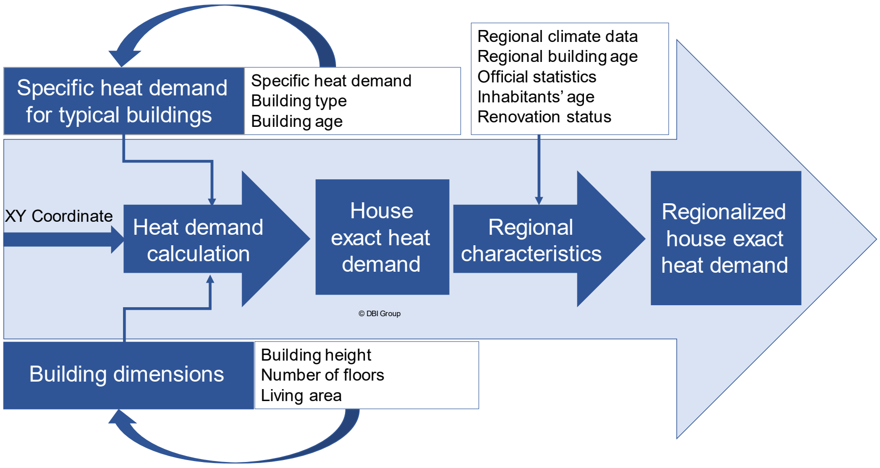

Figure 41: Algorithm to predict address-specific heating demands based on geospatial and statistical data
Source: Thomas Wenzel, DBI Group (own illustration)

Supplying selected quarters with heat from mine water using an ATES-System causes the mine / storage to cool down over the long term. To feed the system with more renewable heat, suitable heat sources for a seasonal feed-in the ATES will be identified, such as:

1. solar thermal potentials in the case study area, especially roof solar thermal potentials,
2. cooling demands per building (residential/non-residential),
3. waste heat potentials from nearby industries (metal-, food-, glass-, and paper industries) as well as
4. surpluses or curtailed renewable electricity potentials (mainly photovoltaic and wind).

Many distinctions are made for each potential. For example, solar thermal energy will be utilized only on the roofs of buildings (Figure 2, right image) because the whole energy concept relies on a grid-based heating supply and solar thermal yields can be fed directly into the grid and the storage system. The former analysed heat demand per building is shown in the left image of figure 2.

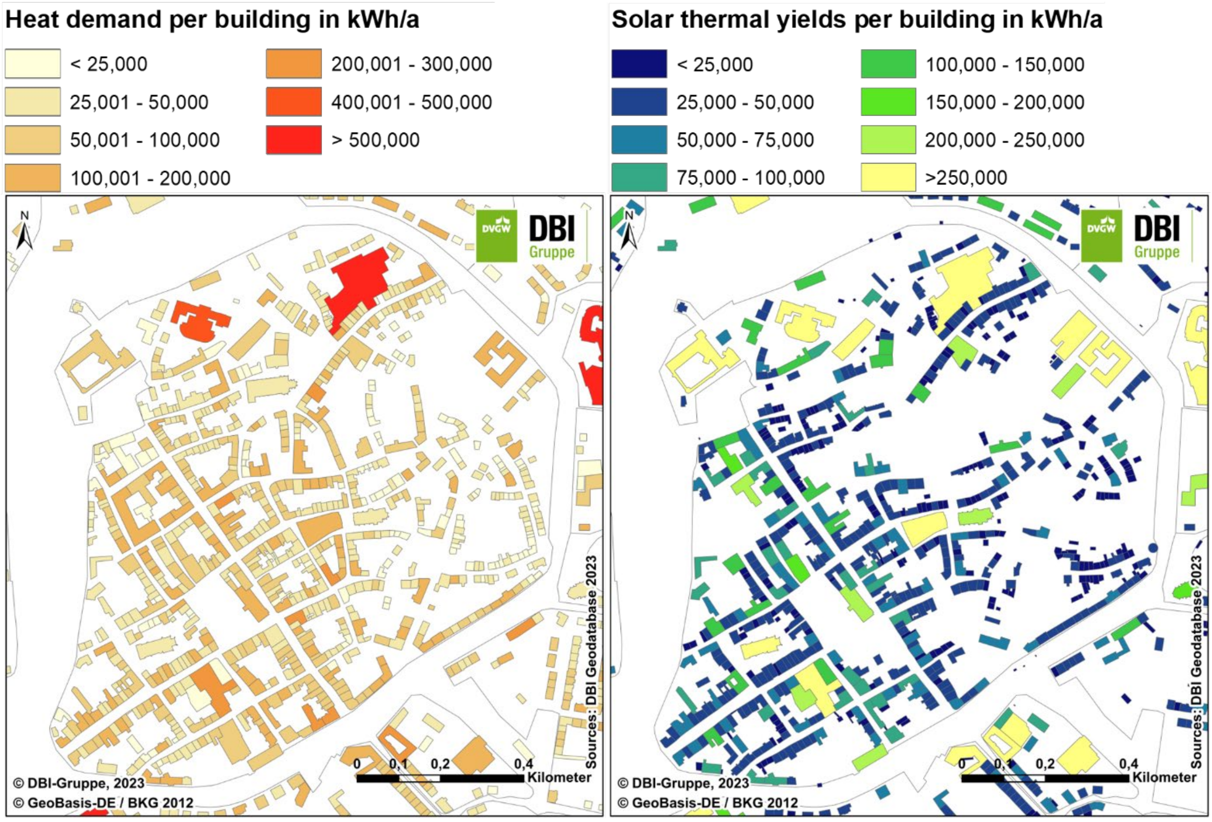

Figure 42: Comparison of heating demands (left picture) and solar thermal yields (right picture) per building in the investigation area the historic old town in Freiberg/Saxony (Germany)
Source: Thomas Wenzel, DBI Group (own illustration)

Local balancing with load profiles and initial results

Important for the integration of renewable energies into heating networks is the amount of energy available to supply the consumers and match their heat demand, as well as the temporal and spatial overlapping of potential and demand. In the heating sector, there is a seasonal offset between supply (green heat) and demand (heating energy requirements), which must be balanced by means of storage solutions and grid infrastructures.

For this reason, the results of the analyses were applied in a first step to be able to design the heating network accordingly. The heat demand and heat yield analyses are plotted and balanced over a year (Figure 3). The analysis considers that heat is only fed into the storage, if the yield from the solar thermal systems is not previously consumed by each building itself. Additionally, the diagram shows a draft for modelled cooling demands, however, in this case this parameter is not very important for the future grid-based system sustainability. For the other feed-in options, such as industrial waste heat and surpluses/curtailed energy from renewable energy systems, the analysis will be carried out further in the project. In total the heat withdrawal stays at 24,87 GWh/a, with a storage regeneration of 12,58 GWh/a (considering heat injection and the natural geothermal heat transmission).

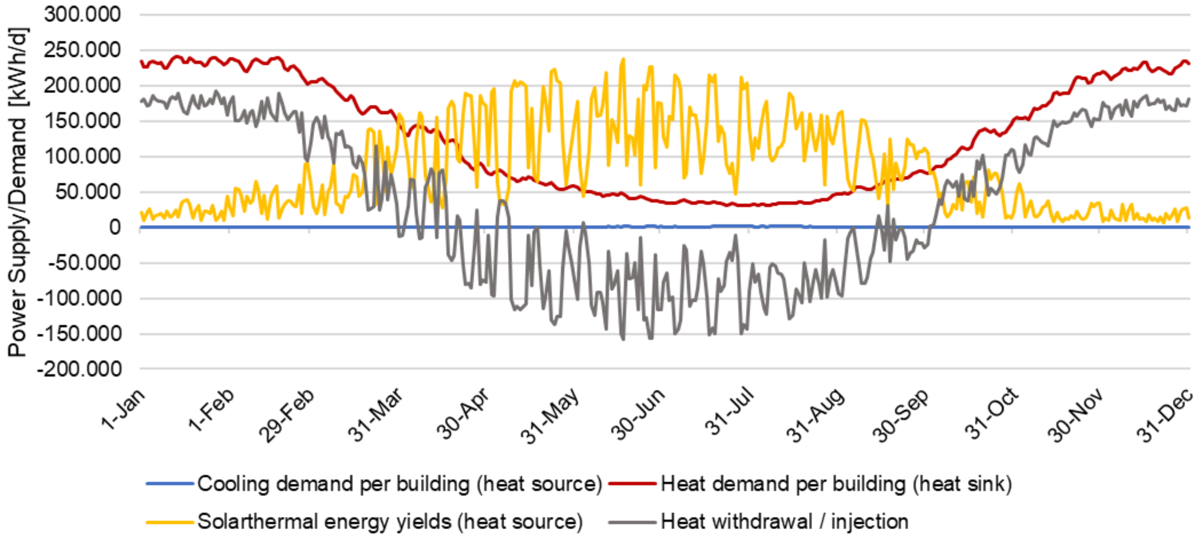

Figure 43: Seasonal progression of cooling requirements, heating requirements, solar thermal yields and the resulting heat withdrawals / injections
Source: Thomas Wenzel, DBI Group (own illustration)

In this first draft, storage losses are not yet considered. The effects of the other heat sources (waste heat, cooling demands and electric surpluses/curtailed energy) will be analyzed further in the project to gain a complete understanding of the necessity of a successful future ATES energy system design. Sub-surface analyses carried out by the project partners also play a major role to include characteristic values in the algorithm model.

5.4.2 Contribution to Solar Energy Buildings

- primary contribution
- secondary contribution

renewable energy generation

heating and or cooling

thermal energy storage

electrical energy storage

building construction/renovation

energy self-resilience

thermal comfort

5.4.3 References

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A main aspect of this report is the market potential analysis derived from the amassed data. By synthesizing information from the technology evaluations, case studies, and expert knowledge, the report provides strategic insights into the growth prospects of individual technologies. The market potential analysis not only identifies key opportunities but also highlights challenges and areas.

The research also focuses on the markets of four specific countries, providing an examination of the solar technology landscape within each. The depth of this investigation is essential for understanding the global applicability and regional nuances influencing the adoption of solar energy in building structures.

To enhance accessibility and comprehension, the report employs a visual representation of results through a technology radar. This tool serves as a comprehensive guide for stakeholders, offering a clear visualization of technological trends, their current usage, and future potential. For the most widely adopted technologies, the report goes a step further by providing additional information on their application, benefits, and potential drawbacks.

In conclusion, this research report serves as a valuable resource for industry stakeholders, policymakers, and investors seeking to navigate the evolving landscape of SEBs. By providing a detailed analysis of current technologies, market dynamics, and potential future trends, the report equips its audience with the insights needed to make informed decisions in fostering sustainable and low-carbon building practices.