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THESEUS

Hub4Circularity

A First of a kind Hub for circularity demonstrator for Attica and peripheral regions

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Solar thermal technology v1

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Publishable summary

Deliverable D6.2, entitled “Solar Thermal v1”, was developed within the framework of Work Package 6 (WP6), “Symbiotic Energy Flows”. It constitutes the first deliverable in a three-part series dedicated to investigating the utilization of solar thermal energy for addressing heating and cooling demands, with a particular focus on district heating applications. This series of deliverables is closely associated with the practical deployment and operation of the corresponding pilot application in Ptolemaida, involving the installation and commissioning of a 1 MW solar thermal park. The overarching objective of this deliverable series is to assess the technical feasibility, operational performance and integration potential of solar thermal technologies across applications.

This deliverable primarily addresses the theoretical and technical background of solar thermal technology. It provides a comprehensive analysis of implementation methodologies, technological prospects, system architectures and key parameters associated with the deployment of solar thermal systems for heating and cooling applications. Furthermore, the report investigates potential thermal energy storage strategies that may be integrated with solar thermal systems in order to enhance flexibility. In addition, the deliverable presents an overview of the specific solar thermal technology selected for the field implementation within the pilot application.

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Abbreviations

Abbreviations	Full name
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CDD	Cooling Degree Days
COP	Coefficient of Performance
CPC	Compound Parabolic Concentrator
CSP	Concentrating Solar Power
CST	Concentrating Solar Thermal
DC	District Cooling
DHI	Diffuse Horizontal Irradiance
DHW	Domestic Hot Water
DNI	Direct Normal Irradiance
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
GHI	Global Horizontal Irradiance
HVFP	High-Vacuum Flat Plate
KAUST	King Abdullah University of Science and Technology
LCOC	Levelised Cost of Cooling
LFR	Linear Fresnel Reflector
PCM	Phase Change Material
PTC	Parabolic Trough Collector
PTES	Pit Thermal Energy Storage
SF	Solar Fraction

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TAC	Thermally activated Cooling
TES	Thermal Energy Storage
TES	Thermal Energy Storage

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1 Abstract

Deliverable D6.2, entitled “Solar Thermal v1”, was developed within the framework of Work Package 6 (WP6), “Symbiotic Energy Flows”. It constitutes the first deliverable in a three-part series dedicated to investigating the utilization of solar thermal energy for addressing heating and cooling demands, with a particular focus on district heating applications. This series of deliverables is closely associated with the practical deployment and operation of the corresponding pilot application in Ptolemaida, involving the installation and commissioning of a 1 MW solar thermal park. The overarching objective of this deliverable series is to assess the technical feasibility, operational performance and integration potential of solar thermal technologies across applications.

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2 Introduction

The utilization of solar energy has constituted a fundamental pillar of renewable and sustainable energy generation for several decades, both at international and national levels. Extensive deployment of large-scale photovoltaic parks has significantly contributed to green electricity production, while solar thermal technologies for domestic and industrial hot water generation have also reached a high degree of technological maturity and market penetration.

However, two important dimensions of solar thermal technology remain comparatively underexplored and insufficiently implemented at large scale. The first concerns the utilization of solar thermal energy for cooling applications, while the second involves the integration of solar thermal systems into district heating infrastructures.

The development of an integrated framework for the holistic utilization of solar thermal energy represents an innovative and highly promising approach capable of opening new pathways toward advanced sustainable energy systems. Such a concept establishes the foundation for the development of a flexible and multifunctional energy hub, based on the circular management and optimized utilization of thermal energy flows generated through solar resources. At the core of this approach lies a solar thermal installation designed to generate the required—and potentially surplus—thermal energy by harnessing available solar irradiance. The produced thermal energy can be directly supplied to end users to satisfy heating demands or alternatively injected into a district heating network. Such integration enhances the renewable penetration of district heating systems and contributes substantially to their decarbonisation and environmental sustainability. Simultaneously, during periods in which energy demand shifts toward cooling applications the produced thermal output can be utilized as an input source for chiller systems, converting the available heat cooling capacity, thereby satisfying cooling demands while simultaneously improving overall system performance.

A large-scale implementation, testing and validation of such an integrated energy model could provide a highly valuable benchmark and practical demonstration case for future deployment. Following adaptation to different parameters and capabilities, this framework could be replicated across a wide range of applications, enabling the development of multiple small- or large-scale green energy hubs that combine solar thermal generation with district heating and cooling systems.

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3 Solar Thermal and Cooling

3.1 Solar Thermal Systems

Solar thermal technology encompasses a broad class of systems that capture radiant energy from the sun and convert it into useful heat. Unlike photovoltaic systems, which convert solar radiation into electricity, solar thermal systems deliver heat directly as hot water, steam, or high-temperature gas for use in domestic hot water (DHW) supply, space heating and cooling, industrial process heat and large-scale power generation via the steam-Rankine or other thermodynamic cycles.

The defining characteristic of all solar thermal systems is the solar collector, which is a device that absorbs incident solar radiation and transfers the resulting heat to a working fluid (typically water, water-glycol, or a synthetic heat transfer fluid). Collectors vary widely in design, operating temperature, optical concentration ratio and cost, and are selected according to the temperature level required by the end application.

Solar thermal systems operate across a broad range of temperatures, commonly classified as:

- **Low-temperature solar thermal (<80°C):** Flat-plate and evacuated-tube collectors for DHW, space heating, swimming pools and low-temperature district heating
- **Medium-temperature solar thermal (80–250°C):** Compound parabolic concentrators and parabolic trough collectors for industrial process heat, solar cooling (via absorption chillers) and district heating
- **High-temperature concentrated solar power (>250°C):** Parabolic troughs, linear Fresnel reflectors, solar towers and dish systems for utility-scale electricity generation, often with integrated thermal energy storage

The main system-level challenge of solar thermal is the inherent temporal mismatch between solar resource availability governed by irradiance, day length and cloud cover and the demand profile of the connected load. This mismatch is addressed through thermal energy storage (TES), from diurnal buffer tanks serving DHW systems to large-scale seasonal pit or aquifer storage for solar district heating. The interaction between solar thermal generation and TES is therefore central to system design and performance.

The key performance parameter of a solar thermal system is the solar fraction, which reflects the proportion of total annual thermal demand met by solar energy. The remainder is met by an auxiliary or back-up heat source (boiler, heat pump, district heat, or combined heat and power). System design is optimised to maximise the solar fraction within economic and spatial constraints.

The principal solar collector technologies and their operating temperature ranges are summarised in the table below:

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Table 1. Summarize of the main solar collector technologies

Collector Type	Temp. Range	Efficiency	Typical Application
Flat Plate Collector (FPC)	30–80°C	50–75%	• DHW • Space heating • Low-temp process heat
Evacuated Tube Collector (ETC)	50–120°C	55–70%	• DHW • District heating • Industrial process heat
Compound Parabolic Concentrator (CPC)	80–200°C	50–65%	• Process heat • Cooling (absorption) • District heating
Parabolic Trough Collector (PTC)	150–400°C	60–75%	• Industrial process heat • Concentrating solar power (CSP) electricity generation
Linear Fresnel Reflector (LFR)	150–300°C	40–60%	• Industrial steam • CSP
Solar Tower / Central Receiver	400–1,000°C+	Up to 80% (peak)	• Utility-scale CSP electricity

Technical Parameters

The performance of a solar thermal system is characterised by a set of interrelated technical and optical parameters. As with thermal energy storage, these parameters must be evaluated in the context of the specific installation, the local solar resource (irradiance levels, direct vs. diffuse split), load profile, operating temperatures and system configuration as absolute values are not transferable between different applications or climatic contexts.

- Collector Efficiency

The instantaneous thermal efficiency (η) of a solar collector is defined as the ratio of useful heat output to incident solar irradiance on the collector aperture and the calculation equation is:

$$\eta = \eta_o - a_1 \cdot (T_m - T_a) / G - a_2 \cdot (T_m - T_a)^2 / G \quad (1)$$

where:

η_o: the zero-loss (optical) efficiency (the fraction of incident radiation absorbed at zero temperature differential)
a_1: the first-order heat loss coefficient (W/m²·K)
T_m : the mean fluid temperature (°C)
T_a : the ambient temperature (°C)
G: the incident solar irradiance (W/m²)
a_2: is the second-order heat loss coefficient (W/m²·K²)

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The efficiency decreases as the mean fluid temperature rises above ambient, or as irradiance falls, representing the fundamental trade-off between operating temperature and useful thermal output.

- Solar Irradiance and Resource

The annual performance of a solar thermal system is strongly influenced by the available solar resource at the installation site, which is characterized by several key solar radiation components. The most important parameters are:

- **Global Horizontal Irradiance (GHI)**: the total solar radiation incident on a horizontal surface, including both direct beam and diffuse radiation components
- **Direct Normal Irradiance (DNI)**: the direct solar radiation received on a surface oriented perpendicular to the sun's rays. This parameter is particularly important for concentrating solar collectors, which rely exclusively on direct radiation for efficient operation
- **Diffuse Horizontal Irradiance (DHI)**: the portion of solar radiation scattered by atmospheric particles and clouds before reaching the Earth's surface. This component can be effectively utilized by non-concentrating collector technologies

Non-concentrating collectors (flat-plate, evacuated tube) can use both direct and diffuse radiation, making them suitable across a wide range of climates including Northern Europe and high-latitude sites. Concentrating collectors (parabolic trough, linear Fresnel, solar tower) require direct beam radiation and are therefore restricted to high-DNI locations, typically arid and semi-arid regions at low to mid latitudes (DNI > 1,800 kWh/m²/year).

- Solar Fraction and System Sizing

The solar fraction (SF) is the primary performance metric of a solar thermal system, defined as the ratio of annual solar heat delivery to total annual heat demand. For domestic hot water systems, solar fractions of 50–70% are typical in Central and Northern Europe with appropriate storage. For solar district heating with seasonal storage, solar fractions of 50–70% are achievable at larger scale, with demonstration systems approaching 100%.

System sizing is governed by the trade-off between increasing collector area and storage volume (which raise solar fraction and upfront capital cost) against diminishing marginal returns as the system becomes oversized relative to base demand. Economic optimisation typically targets the lowest Levelised Cost of Heat (LCOH) rather than maximum solar fraction. Indicative sizing parameters are provided in the table below:

Table 2. Indicative sizing parameters of solar collectors

Application	Collector Area Rule-of-Thumb	Storage Volume	Solar Fraction (typical)
DHW (single family)	1.5–2.5 m² / person	50–75 L / m² collector	50–70% annual
DHW + space heating	3–6 m² / person	75–150 L / m² collector	30–60% annual
Solar District Heating (diurnal TES)	0.2–0.5 m² / MWh annual load	~9 m³ / GWh annual delivery	15–30% annual

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Solar District Heating (seasonal TES)	1.5–4 m² / MWh annual load	~12,000 m³ / GWh annual delivery	50–70% annual
Industrial Process Heat (<100°C)	System-specific (GHI, load profile)	1–4 h storage typical	20–60% annual
Concentrated Solar Power (CSP)	System-specific (DNI, capacity factor)	6–15 h molten salt TES	25–45% capacity factor

- Stagnation and Overheating

A critical design constraint for solar thermal systems, particularly for pressurised systems with large collector fields, is stagnation: the condition reached when the collector is irradiated but no fluid flow occurs (due to pump failure, power outage, or deliberate shutdown). Under stagnation, fluid temperatures can exceed 200°C in evacuated-tube collectors and 150–180°C in flat-plate collectors, potentially causing fluid degradation, pressure relief valve actuation, and damage to collector components.

Stagnation management is addressed through: the use of heat-stable heat transfer fluids (synthetic oils, propylene glycol with appropriate inhibitors); drain-back system designs in which fluid returns to a low-pressure reservoir under gravity when circulation stops; and the use of thermally robust collector materials (borosilicate glass, high-temperature seals). District heating solar installations require particular attention to stagnation management given the scale of collector fields involved.

- Thermal Performance Calculation — Simplified Annual Output

A simplified estimate of annual useful heat output Q_{annual} from a solar collector field can be obtained from the following equation:

$$Q_{annual} = A \cdot H_{annual} \cdot \eta_{sys} \quad (2)$$

where

A: the collector aperture area (m²)
H_{annual}: the annual solar irradiation incident on the tilted collector plane (kWh/m²/year)
η_{sys}: the annual average system efficiency (accounting for collector efficiency at mean operating conditions, pipe losses, storage losses, and auxiliary system consumption)

For flat-plate collectors in Central Europe, H_{annual} typically ranges from 900–1,300 kWh/m²/year (south-facing, optimally tilted), and η_{sys} from 35–55%, yielding specific annual yields of 300–600 kWh/m²/year.

Different Technologies

Solar thermal technology is a well-established and mature solution that has undergone extensive research, experimental validation and technological assessment over several decades. In addition, numerous real-world implementations have been successfully deployed across a broad range of applications. A brief analysis is followed in order to cover the principal commercially deployed and emerging solar thermal technologies,

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spanning domestic, district, industrial and utility-scale applications. Each technology is described in terms of its operating principle, applicable temperature range, key technical characteristics and cost parameters representative installations.

A. Non-Concentrating Solar Thermal Collectors

Flat Plate Collector (FPC)

The flat plate collector is the most widely deployed solar thermal technology worldwide. A glazed, insulated box contains an absorber plate, typically a copper or aluminium sheet with selective coating to maximise solar absorptance and minimise thermal emittance, through which heat transfer fluid circulates. A single or double low-iron glass cover reduces convective and radiative losses from the absorber surface. The technology is robust, well-understood and amenable to building integration (roof-mounting, façade integration). The operating temperature range of the collectors is between 30–80°C, while for low flows the effective operation is approximately 90°C. The optical efficiency η_o of a high-quality FPC is typically 0.75–0.82. The first-order loss coefficient a_1 is 3–5 W/m²·K. FPCs lose efficiency rapidly above approximately 60–70°C above ambient, making them unsuitable for high-temperature process heat applications. Frost protection is provided by propylene glycol antifreeze in the heat transfer loop, with a heat exchanger separating the primary collector loop from the potable water or secondary heating circuit.

Capital cost of FPC systems (installed, including storage and balance of plant) ranges from approximately 500–1,200 €/m² for residential systems in Europe, declining at larger scales for district or industrial applications.

Applications

- ✓ Domestic hot water (DHW)
- ✓ Space heating
- ✓ Swimming pools
- ✓ Low-temperature district heating
- ✓ Low-temperature industrial process heat

Representative installations

- Vojens solar district heating, Denmark (70,000 m² FPC, 500,000 m³ pit storage, 45% solar fraction)
- Graz, Austria (residential solar heating network, 10,000+ installations)
- Widespread deployment across Germany, Austria and Denmark for DHW and space heating

Evacuated Tube Collector (ETC)

Evacuated tube collectors use glass vacuum tubes to eliminate convective heat loss from the absorber. Each tube contains a selective-coated absorber strip and in the most common design, a heat pipe that transfers collected heat to a manifold. The vacuum insulation enables effective operation at temperatures significantly higher than flat-plate collectors and reduces sensitivity to cold ambient temperatures, making ETCs advantageous in Northern European and high-altitude climates. The working temperature varies between 50–120°C, while the heat pipe variants effective to 150°C. The optical efficiency η_o of a high-quality ETC is typically 0.65–0.75 (lower than FPC due to the circular tube geometry reducing effective aperture), but the

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heat loss coefficient is substantially lower (a_1 = 1–2 W/m²·K), yielding higher efficiency at elevated temperature differentials. ETCs are more fragile than FPCs (risk of tube breakage) and can exhibit higher stagnation temperatures (up to 200–250°C), requiring appropriate system design. Individual tube replacement is possible without draining the system.

Capital cost is typically 10–30% higher than comparable FPC systems on a per-m² basis, partially offset by higher specific output at elevated operating temperatures.

Applications

- ✓ Domestic hot water (DHW)
- ✓ Space heating
- ✓ District heating
- ✓ Industrial process heat
- ✓ Solar cooling (absorption)
- ✓ High-performance building systems

Representative installations

- Braedstrup solar district heating, Denmark (33,000 m² ETC, integrated with CHP and seasonal pit storage)
- Widespread deployment in China for DHW (>500 million m² installed nationally)
- Commercial building solar heating systems across Central Europe and Scandinavia

B. Concentrating Solar Thermal (CST) Systems

Compound Parabolic Concentrator (CPC)

CPC collectors use static (non-tracking) or single-axis tracking parabolic reflector troughs to concentrate diffuse and direct solar radiation onto a tubular absorber, achieving concentration ratios of 1.5–5×. This modest concentration, combined with evacuated tube absorbers, enables useful thermal output at temperatures above the effective range of flat-plate collectors without the complexity and cost of dual-axis tracking systems. CPCs are particularly suited to medium-temperature process heat applications (drying, pasteurisation, steam generation at low pressure) and as driving heat source for single-effect absorption cooling systems. The range of the operating temperature is between 80–200°C.

Applications

- ✓ Medium-temperature process heat
- ✓ Solar cooling (absorption chillers)
- ✓ District heating
- ✓ Pre-heating for industrial processes

Representative installations

- Solar cooling demonstration projects across Southern Europe and the Middle East
- Process heat systems in the food and beverage industry

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Parabolic Trough Collector (PTC)

Parabolic trough collectors focus direct normal irradiance onto a linear receiver tube (heat collection element, HCE) using a single-axis tracking parabolic mirror. The HCE consists of a metal absorber tube within an evacuated glass envelope, with selective coating achieving absorptance higher than 0.95 and emittance lower than 0.10 at operating temperatures. Synthetic thermal oil (e.g. Therminol VP-1, Dowtherm A) is the conventional heat transfer fluid for the temperature range 100–400°C. Direct steam generation (DSG) and molten salt (up to 550°C) are alternative approaches. PTC is the most commercially mature concentrating solar technology, with over 5 GW installed worldwide primarily in Spain and the south-western United States.

For industrial process heat below 200°C, smaller-scale industrial PTC installations have been demonstrated in pharmaceutical, food processing, and mining applications. Capital costs for utility CSP with PTC are approximately 3,000–5,000 €/kW installed (including 6–8 h molten salt TES).

Applications

- ✓ Industrial process heat (100–400°C)
- ✓ Utility-scale CSP electricity generation
- ✓ Solar district heating (high-temperature)
- ✓ Solar cooling (double-effect absorption)

Representative installations

- Andasol 1–3, Spain (3 × 50 MW PTC CSP, 7.5 h molten salt TES, operational since 2008–2011)
- SEGS I–IX, Mojave Desert, USA (354 MW total, operational since 1984–1990, longest-operating CSP plants)
- Noor I, Morocco (160 MW PTC, 3 h TES)

Linear Fresnel Reflector (LFR)

Linear Fresnel reflectors use an array of flat or slightly curved mirror strips arranged on a horizontal plane to focus DNI onto a fixed elevated linear absorber (a cavity or tube receiver). The flat mirror geometry allows denser packing than parabolic troughs, reducing land use and structural wind loads, and the fixed receiver simplifies the use of direct steam generation, eliminating the need for an intermediate heat transfer fluid and heat exchanger. These characteristics yield lower capital costs per m² of mirror aperture than PTC, partially offset by lower optical efficiency. The typical operating temperature range between 150–300°C (saturated or slightly superheated steam).

Applications

- ✓ Industrial process steam
- ✓ Utility-scale CSP
- ✓ Direct steam generation for district heating

Representative installations

- Novatec Biosol PE 1, Spain (30 MW, direct steam generation)
- Areva Solar / Kogan Creek, Australia (44 MW steam augmentation for existing coal plant)
- FRESLIME industrial steam project, Belgium

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Solar Tower (Central Receiver System)

Solar tower systems use a large field of individually tracking flat mirrors (heliostats) to focus DNI onto a central receiver mounted atop a tower. The very high concentration ratios achievable (500–1,000×) enable delivery of heat at temperatures well above those of line-focus systems, with corresponding improvements in thermodynamic cycle efficiency. Molten salt (60% $NaNO_3$ / 40% KNO_3) at 565°C is the most commercially deployed receiver fluid, simultaneously serving as the thermal energy storage medium. This direct integration of receiver and storage fluid eliminates the need for an intermediate heat exchanger and enables cost-effective TES at scale. The operation temperature fluctuates from 400°C to 600°C for molten salt, while is up to 1,000°C for air or pressurised water in steam receivers

The heliostat field represents approximately 40–50% of total capital cost. Advanced designs using supercritical CO_2 (sCO_2) power cycles, at temperatures above 700°C, are in demonstration phase, promising step-change improvements in efficiency. Capital costs for current commercial projects are approximately 4,000–7,000 €/kW (with 10–15 h TES).

Applications

- ✓ Utility-scale CSP generation (50–150 + MW)
- ✓ High-temperature industrial process heat

Representative installations

- Gemasolar, Spain (19.9 MW, 15 h molten salt TES, first commercial tower with full load 24-hour operation demonstrated)
- Ivanpah, California (392 MW, three towers, no TES)
- Noor III, Morocco (150 MW, 7.5 h molten salt TES)
- Crescent Dunes, Nevada (110 MW, 10 h molten salt TES)

C. High-Vacuum Flat Plate (HVFP) Solar Thermal

The following case studies present the practical implementation and operational performance of TVP Solar's High-Vacuum Flat Plate (HVFP) MT-Power technology in district heating and solar cooling applications. These real-world deployments provide valuable evidence regarding the technology's thermal performance, operational reliability and applicability under varying system configurations and environmental conditions. Their relevance to the Theseus project is particularly significant, as they demonstrate the capability of the technology to operate effectively across diverse climatic contexts, thereby offering important insights into its scalability, adaptability and potential for integration into advanced sustainable energy systems.

Sondershausen, Germany — Solar District Heating (2024)

The Sondershausen solar district heating project, commissioned in 2024, represents a high-performance integration of HVFP solar thermal technology into an existing district heating network. The installation comprises 3,105 high-vacuum solar panels across a collector area of 6,086 m², delivering a total thermal capacity of 4.7 MW_{th}. The system generates approximately 3,250 MWh annually under standard conditions, with robust performance even under adverse weather scenarios. Heat is delivered at temperatures up to 95°C, supported by a 1,000 m³ thermal energy storage system. From an environmental and economic perspective, the project reduces natural gas consumption by approximately 368,000 m³ per year and cuts

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CO_2 emissions by 732 tonnes annually. The system demonstrates strong reliability, high efficiency in low-irradiance conditions and seamless integration into the district heating infrastructure.

Groningen, Netherlands — Large-Scale Solar District Heating (2022–2023)

The Groningen solar district heating system is one of the largest HVFP installations globally, commissioned between 2022 and 2023. The plant includes 48,000 m² of solar collectors across a 12-hectare site, with a peak thermal capacity of 37 MW_{th} and a 6,000 m³ storage tank. Annual energy production reaches approximately 25,000 MWh, delivering hot water at 75°C directly into the district heating network. The system achieves significant economic benefits, reducing heating costs by approximately 20% compared to natural gas tariffs. Environmental performance is substantial, with annual savings of over 3 million m³ of natural gas and CO_2 reductions exceeding 6,100 tonnes. The project highlights the scalability of HVFP solar thermal solutions for large urban heating networks.

Racconigi, Italy — Compact Solar District Heating (2024)

The Racconigi solar district heating project, commissioned in 2024, demonstrates the viability of HVFP technology at smaller municipal scale. The system consists of 1,029 m² of collectors with a peak capacity of 0.7 MW_{th}. It produces approximately 920 MWh of thermal energy annually, supplying hot water at 75°C directly to the district heating network. Despite its smaller scale, the system delivers measurable sustainability benefits, reducing natural gas consumption by 122,000 m³ annually and lowering CO_2 emissions by 240 tonnes. This project demonstrates the viability of solar district heating solutions for smaller municipalities, offering a cost-effective and environmentally sustainable alternative to conventional heating sources.

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3.2 Solar Cooling Systems

Solar cooling has emerged as one of several promising renewable technologies, answering Europe's and especially Southern Europe's growing need for clean, affordable and secure cooling. In a solar cooling system, fields of solar collectors (flat-plate, evacuated tube or concentrating types) capture sunlight and convert it into heat, which in turn drives a thermally activated cooling machine — most commonly an absorption or adsorption chiller. The chilled water produced is either fed directly into a district cooling (DC) network or used to serve building-level air-conditioning and refrigeration loads. Integrating large-scale solar cooling plants into existing district cooling infrastructure can substitute electricity-intensive conventional chillers and thereby reduce greenhouse gas emissions, peak electricity demand and operating costs.

Unlike solar district heating, which faces a seasonal mismatch challenge (maximum solar yield in summer, maximum heat demand in winter), solar cooling is inherently demand-synchronous, as solar irradiation peaks in summer and so does cooling demand. This natural alignment reduces the need for large-scale thermal storage and improves system economics. Nonetheless, solar cooling at district scale remains less commercially mature than solar district heating, representing both a challenge and a significant opportunity for cities across Europe and the Mediterranean region.

Solar cooling systems use solar-generated heat rather than electricity as the primary energy input to drive a thermodynamic cooling cycle. This is thermally activated cooling (TAC) and it contrasts fundamentally with conventional vapour-compression cooling (the technology in standard air conditioners and chillers), which is electricity-driven. The main solar cooling technology pathways are:

1. Absorption Chillers

An absorption chiller uses a refrigerant-absorbent working pair most commonly lithium bromide / water ($LiBr$-H_2O) for air conditioning (cooling down to ~5–7 °C) or ammonia / water (NH_3-H_2O) for industrial/process cooling (below 0°C). Heat from solar collectors drives the desorption of refrigerant from the absorbent and the cycle produces chilled water. Absorption chillers are the most widely deployed solar cooling technology and are commercially mature for large capacities (above ~100 kW cooling). Absorption chillers can be classified into three primary categories based on the number of thermal generation stages incorporated into their thermodynamic cycle.

- **Single-effect absorption chillers:** Absorption chillers using a single thermal generation stage. COP (Coefficient of Performance, ratio of cooling output to heat input) is approximately 0.6–0.8, while the required driving temperatures are between 70–95 °C. Are compatible with flat-plate or evacuated tube collectors and are suitable for building and district cooling applications.
- **Double-effect absorption chillers:** Systems employing two sequential heat recovery/generation stages with a COP of approximately 1.2–1.4. Require driving temperatures of 130–170 °C and are compatible with concentrating solar collectors (e.g. parabolic trough, Fresnel) or high-performance evacuated tubes. They perform higher efficiency but greater complexity and higher collector cost.
- **Triple-effect absorption chillers:** Advanced absorption systems utilizing three heat recovery stages, with COP approaching 1.7–2.0 and very high driving temperatures (>200 °C). Potentially very efficient but require advanced concentrating solar technology.

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2. Adsorption Chillers

Adsorption chillers use solid adsorbent materials (typically silica gel / water or zeolite / water) operating in a cyclic adsorption-desorption process. COP is typically 0.5–0.7, similar to single-effect absorption, but the key advantage is the operation at lower driving temperatures (55–85 °C), making them particularly compatible with flat-plate collectors and solar thermal systems with modest operating temperatures. They are simpler and more robust (fewer corrosion issues than LiBr) but have lower specific capacity and higher volume per kW than absorption devices. Adsorption chillers are commercially available in small-to-medium sizes (10–200 kW cooling) and are growing in market share for solar cooling applications.

3. Desiccant Cooling (Open Cycle)

Desiccant systems use hygroscopic materials solid (desiccant wheel / rotary dehumidifier) or liquid to dry incoming air by adsorbing moisture. Then use evaporative cooling to achieve comfort temperatures and solar heat regenerates the desiccant. This is an open-cycle system that works directly with air rather than water, making it suitable for air-handling unit integration. COP (defined differently for open cycle systems, as sensible cooling ratio) can exceed 1 in humid climates where dehumidification is the dominant need. Desiccant cooling is particularly valuable in hot and humid climates (Mediterranean coasts, tropical zones) where both sensible cooling and dehumidification are required simultaneously. Driving temperatures rate between 50 and 80 °C.

4. Ejector Cooling

Ejector cooling systems use a thermal ejector (driven by pressurized vapor from solar heat) to produce cooling via a refrigerant cycle. COP is relatively low (0.2–0.5) but systems are very simple, with no moving parts and inexpensive. They are technically viable but commercially less mature, mostly at research/demonstration stage. Driving temperatures are 70–120 °C, depending on design.

Table 3. Comparison of main solar cooling technologies

Technology	Typical COP	Driving Temperature	Commercial Maturity
Single-effect Absorption	0.6 – 0.8	70 – 95 °C	Commercially mature (large scale)
Double-effect Absorption	1.2 – 1.4	130 – 170 °C	Commercial, higher complexity
Adsorption	0.5 – 0.7	55 – 85 °C	Commercial (small-medium scale)
Desiccant (open cycle)	0.5 – 1.0+	50 – 80 °C	Commercial, humid climates
Ejector	0.2 – 0.5	70 – 120 °C	Mostly demo / R&D stage

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Technical Parameters

The operational performance of chiller systems is strongly influenced by several key parameters that can significantly enhance or deteriorate system efficiency and overall functionality. Among the most critical performance indicators are the Coefficient of Performance (COP), the driving temperature and the Solar Fraction (SF).

- Coefficient of Performance (COP)

The Coefficient of Performance constitutes the fundamental thermodynamic efficiency metric for absorption cooling systems, expressing the ratio of the useful cooling effect delivered to the conditioned space ($\dot{Q}_{cool}$) relative to the thermal energy supplied to the generator by the solar heat source ($\dot{Q}_{drive}$):

$$COP = \dot{Q}_{cool} / \dot{Q}_{drive} \quad (3)$$

Unlike vapor-compression systems, where performance is benchmarked against electrical work input, absorption chillers are thermally driven and their COP is therefore a measure of how effectively low- to medium-grade heat is converted into refrigeration. It is important to note that the COP as defined above is strictly a first-law (energy) efficiency indicator and does not capture irreversibilities within the cycle, second-law (exergetic) analyses are increasingly employed in the literature to evaluate the thermodynamic quality of the conversion process and identify the dominant sources of irreversibility.

- **Single-effect** lithium bromide water (LiBr–H_2O) absorption chillers, which represent the most commercially mature and widely deployed technology in solar cooling applications, operate with COP values typically in the range of **0.6–0.8**. The relatively modest COP is a direct consequence of the single generator absorber loop, which limits the extent to which the driving heat can be exploited before it is rejected to the heat sink.
- **Double-effect** machines introduce a second generator stage, wherein the high-pressure refrigerant vapor produced in the primary (high-temperature) generator serves as the heat source for a secondary (low-temperature) generator, effectively recycling thermal energy within the cycle. This internal heat cascade elevates typical COP values to **1.0–1.4**, representing a substantial improvement in thermal utilization efficiency. The trade-off, however, is a requirement for significantly higher driving temperatures, which imposes more stringent demands on the solar collector subsystem.
- **Triple-effect** and advanced multi-effect configurations, currently at the frontier of commercial development, achieve COP values **exceeding 1.6** by further extending the internal heat recovery chain. These systems, while thermodynamically attractive, entail considerably greater mechanical and thermochemical complexity, higher operating pressures, and more demanding material requirements, all of which affect both capital cost and system reliability. Their integration with solar thermal fields is an active area of research, particularly in the context of concentrating solar collector arrays.

- Driving Temperature

The driving temperature, defined as the minimum heat source temperature required at the generator inlet to maintain stable thermodynamic operation, constitutes a critical design and operational parameter in

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thermally driven cooling systems. It directly influences the selection of appropriate solar collector technologies and plays a decisive role in determining the feasibility and effectiveness of system integration under specific climatic and operating conditions.

- **Single-effect** LiBr–H_2O chillers, stable generator operation requires inlet temperatures in the range of approximately **75–90 °C**. This temperature window is comfortably achievable with evacuated tube collectors (ETCs) and high-performance flat-plate collectors (FPCs) under typical solar irradiance conditions in Mediterranean, subtropical and semi-arid climates. The low thermal threshold is one of the main reasons single-effect absorption technology dominates the current solar cooling market.
- **Double-effect** chillers demand significantly elevated generator temperatures, typically **140–180 °C**, which lie beyond the practical operating range of conventional non-concentrating collectors. At this level, medium-concentration optical systems are required, most notably compound parabolic concentrators (CPCs), which are capable of achieving the requisite temperatures without full-tracking mechanisms, making them a pragmatic choice for building-integrated installations. Evacuated tube collectors with integrated reflectors may also achieve the lower end of this range under high direct normal irradiance (DNI) conditions.
- **Triple-effect** and advanced cycle systems require driving temperatures that may reach **200–250 °C** or above, necessitating line-focus concentrating systems such as parabolic trough collectors (PTCs) or linear Fresnel reflectors (LFRs). These technologies introduce additional system complexity, including single-axis solar tracking, optical alignment maintenance, and heat transfer fluid management, and are generally better suited to centralized or industrial-scale installations than to small building-level systems.

A critical design challenge, regardless of technology tier, is ensuring that the solar collector field reliably delivers the required driving temperature across the full range of seasonal and diurnal variation in solar irradiance. Collector field sizing must account for diffuse radiation conditions, incidence angle modifiers, thermal losses at elevated operating temperatures and the possibility of stagnation during periods of low demand. Thermal storage integration is an essential complementary measure to buffer supply demand mismatches.

- Solar Fraction (SF)

The solar fraction is a system-level performance indicator that quantifies the proportion of the total annual cooling energy demand satisfied by the solar thermal subsystem:

$$SF = Q_{solar} / Q_{total} \quad (4)$$

where

Q_{solar}: the solar-derived cooling energy delivered over the evaluation period (typically one year)
Q_{total}: the total cooling energy demand of the building or process

The solar fraction thus provides a direct measure of the degree of decarbonisation and fossil fuel displacement achieved by the solar cooling system, and it serves as a key input to life-cycle economic and environmental assessments.

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Solar fraction is not a fixed system property but an outcome of the integrated interaction among multiple design variables such as collector field area and tilt, thermal storage volume and stratification characteristics, chiller nominal capacity and part-load behavior, building cooling load profile and local solar resource availability. As the collector area and storage capacity increase for a given demand profile, the solar fraction rises asymptotically toward unity; however, the marginal increase in SF per unit of additional collector area diminishes progressively, leading to a well-defined economic optimum beyond which additional investment yields disproportionately small energy benefits. In well-designed systems deployed in Mediterranean and Middle Eastern climates regions characterized by high summer solar irradiance coinciding with peak cooling demand solar fractions of **0.4–0.8** are commonly reported in the literature and in monitored demonstration projects. The upper range of this interval is typically associated with large-scale systems incorporating substantial thermal storage, high-performance concentrating collectors, and buildings with relatively uniform seasonal cooling loads. Conversely, systems with limited storage or highly variable demand profiles tend to achieve solar fractions in the lower portion of this range. From a design optimization standpoint, the solar fraction must be evaluated in conjunction with the solar collector efficiency, the chiller part-load performance curve and the auxiliary backup system capacity. In practice, a conventional auxiliary heat source (gas boiler, district heat or electric heater) is invariably included to ensure uninterrupted cooling supply during periods of insufficient solar radiation and the sizing of this auxiliary component is directly informed by the target solar fraction. Optimisation studies frequently employ dynamic simulation tools (TRNSYS, EnergyPlus, Polysun) to identify the collector area–storage volume combination that minimizes the levelised cost of cooling (LCOC) for a specified minimum solar fraction constraint.

These three parameters COP, driving temperature and solar fraction are fundamentally interlinked: the choice of chiller effect determines the COP ceiling and the required driving temperature, which in turn governs the collector technology selection and the attainable solar fraction under a given climate. Their simultaneous optimisation constitutes the central engineering challenge in the design of solar-cooling absorption systems.

Case Studies

Solar cooling technologies have been extensively developed and deployed worldwide, with numerous installations demonstrating reliable and efficient operation under real-world conditions. Although these systems have primarily been implemented in Mediterranean and high-temperature climatic zones, where favourable solar resources align with peak cooling loads, their applicability has also been validated in colder regions. Some representative implementations are briefly discussed below.

King Abdullah University, Saudi Arabia - Large-Scale Absorption Cooling

King Abdullah University of Science and Technology (KAUST) in Thuwal, Saudi Arabia, operates what was at commissioning (2009) one of the world's largest solar cooling systems. The installation includes 6,600 m² of parabolic trough collectors driving four double-effect LiBr absorption chillers with a combined nominal capacity of 2,000 kW (570 RT), integrated into the campus district cooling network.

The system operates at driving temperatures of 155–180°C and achieves a thermal COP of 1.25. Annual solar cooling output exceeds 2,400 MWh, displacing approximately 680,000 kWh of electrical energy for compression cooling. Given the extreme climate - annual cooling degree days (CDD) exceeding 4,000 - the solar cooling fraction of the campus totals approximately 12%, with the solar field covering peak loads on the highest-demand days. The project demonstrated the scalability of concentrating solar thermal cooling for large institutional applications in hot arid climates.

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Brescia, Italy - SolarNext AG Hotel Fontanella

A 4-star hotel in Brescia, northern Italy, installed a solar cooling and heating system in 2012 consisting of 200 m² of flat-plate collectors, a 15 kW adsorption chiller (silica gel/water, COP = 0.60) and backup heat pump. The system provides cooling for 32 guest rooms from May to September and DHW year-round. A 2 m³ cold buffer and 3.5 m³ hot buffer stabilize chiller operation.

Measured seasonal performance showed a solar cooling fraction of 61% and annual CO_2 savings of 18.5 tones. Investment was EUR 185,000 with a payback period of 9.5 years including incentives from Italian Government (Conto Termico incentives). This case study is frequently cited in IEA SHC literature as demonstrating the technical maturity of adsorption-based solar cooling for small-to-medium commercial buildings.

Freiburg, Germany - IEA SHC Task 38 PSE AG Office Building

The Physikalisch Meteorologisches Observatorium Davos (PMOD) and IEA Solar Heating and Cooling programme Task 38 documented a benchmark solar cooling installation at PSE AG's office building in Freiburg, Germany. The system deploys 140 m² of vacuum tube collectors driving a 30 kW single-effect LiBr absorption chiller (COP = 0.73), with a 1.5 m³ hot water buffer and a 2.5 m³ cold water storage vessel.

Annual monitoring data showed a solar fraction for cooling of 68%, with a specific collector yield of 610 kWh/m²/yr. Primary energy savings of 52% relative to a conventional split-unit system were measured over a three-year monitoring period. The system also provided solar space heating with a separate 5 m³ seasonal storage tank, achieving an integrated solar fraction for heating and cooling of 58%. Key lessons included the importance of hydraulic balancing and advanced control strategies to maximize chiller operating hours.

Abu Dhabi - Office Building, Hybrid Solar System with Ice Storage

A single-floor office building in Abu Dhabi with a peak cooling load of 70 kW was retrofitted with a hybrid solar-powered cooling system incorporating ice thermal storage. The solar collector array supplied heat to an absorption chiller during daylight hours, while surplus solar energy was used to produce ice during off-peak periods. The ice store then discharged during peak afternoon demand, reducing instantaneous chiller capacity requirements. Compared to a conventional vapor compression baseline, the system achieved a 38% reduction in annual energy consumption and a 40% reduction in CO_2 emissions, demonstrating that even moderate solar fractions can yield significant environmental and economic benefits in high-irradiance, high-demand climates.

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3.3 Storage

Thermal Energy Storage (TES) refers to a set of technologies that enable the temporary accumulation of thermal energy, in the form of heat or cold for use at a later time. By decoupling the moment of energy production from the moment of consumption, TES systems enhance the flexibility, efficiency and reliability of energy networks. The core function of a TES system is to shift thermal energy in time, complementing distribution infrastructure that moves energy in space.

TES can operate across a broad range of temperatures, serving both heating and cooling applications:

- **High-temperature heat storage (>100°C)**: Industrial process heat, concentrated solar power, district heating
- **Medium-temperature heat storage (40–100°C)**: District heating and cooling networks, solar thermal, combined heat and power integration
- **Low-temperature / cooling storage (<15°C)**: District cooling, building air-conditioning, cold chain logistics, data center cooling
- **Near-ambient storage (10–30°C)**: Ground-source heat pump systems, aquifer and borehole storage for combined heating and cooling

TES systems are broadly classified by their storage mechanism into three categories:

- **Sensible heat storage**: Energy is stored as a temperature change in a liquid or solid medium (e.g. water, rock, soil). This is the most commercially mature category
- **Latent heat storage**: Energy is stored as a phase change (typically solid-to-liquid) in a Phase Change Material (PCM). Storage occurs at a near-constant temperature, offering high energy density
- **Thermochemical storage**: Energy is stored and released through reversible chemical reactions or sorption processes. This technology remains largely pre-commercial for large-scale applications

In addition to their primary function of load shifting, TES systems provide a range of system-level services including peak shaving to reduce demand charges, arbitrage between low-cost and high-cost energy production periods, improved utilisation of base-load generation assets, integration of variable renewable energy sources, back-up and emergency capacity and reduced mechanical wear through avoidance of frequent start-stop cycling of generation equipment.

Technical Parameters

The performance of a TES system is characterised by a set of interrelated technical parameters. These parameters must always be evaluated in the context of the specific energy system in which the storage is embedded — the prevailing temperature levels, load profiles, and generation mix — as absolute values are not directly transferable between different applications.

- Energy Capacity

For sensible heat storage in water, the stored energy capacity Q (MWh) is:

$$Q = \rho \cdot c_p \cdot V \cdot \Delta T / 3{,}600 \quad (5)$$

where

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ρ: the fluid density (≈ 1 kg/L for water)
c_p: the specific heat capacity (≈ 4.18 kJ/kg·K)
V: the storage volume (m^3)
ΔT: the effective temperature difference (°C) between the charged and discharged states

For PCM systems, latent heat capacity is calculated as the product of storage mass and the specific enthalpy of the phase transition (kJ/kg), typically at a fixed phase-change temperature.

The achievable temperature difference is system-dependent. A district heating system with low return temperatures may sustain a ΔT of 50–60°C, while a district cooling system may operate with a ΔT of only 8–12°C, requiring proportionally larger volumes for equivalent energy capacity.

- Temperature Quality, Stratification and Exergy Loss

Beyond the total quantity of stored energy, the temperature quality — or exergy — of the stored thermal energy is a critical operational parameter. In sensible heat water storage, an ideal system maintains a sharp thermocline separating the charged (hot or cold) zone from the uncharged zone. As turbulence and thermal diffusion progressively widen this boundary, the mixing loss reduces the fraction of stored energy that can be delivered at the required supply temperature, even though the total energy content is unchanged.

For heating applications, a fully mixed storage may require supplementary boosting (via a boiler or heat pump) to raise supply temperatures to network requirements. For cooling applications, the equivalent effect is a rise in the chilled water temperature, reducing cooling effectiveness or requiring additional chiller operation. The practical consequence in both cases is a reduction in the net useful energy delivered and an increase in operating costs.

PCM systems inherently avoid this degradation for the portion of energy stored as latent heat, since the phase transition occurs at a fixed temperature. However, the sensible heat component of a PCM system (heating/cooling the PCM above or below the phase-change temperature) is still subject to mixing losses.

- Thermal Efficiency and Heat Loss

The round-trip thermal efficiency of a TES system is defined as the ratio of useful energy recovered from storage to the total energy charged. Losses arise from two mechanisms, the envelope losses (heat transfer between the storage and its surroundings) and the internal mixing/exergy losses (described above).

Envelope losses are a function of the average storage temperature, ambient temperature, insulated surface area and insulation thermal resistance. For short-duration (diurnal) storage, envelope losses are typically negligible relative to total throughput. For long-duration (seasonal) storage, envelope losses become a primary design constraint, particularly as they act preferentially on the highest-value (hottest or coldest) portion of the stored energy.

For cooling energy storage systems, the thermal gradient is effectively reversed compared to heating applications. In this case, the stored cooling capacity exists at a temperature lower than the ambient environment, while heat transfer from the surroundings into the storage system results in thermal gains that progressively degrade the stored cooling potential. Consequently, parasitic heat ingress becomes the principal mechanism responsible for storage performance deterioration. Although the insulation requirements are conceptually similar to those of thermal storage systems for heating applications, the

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temperature differential driving heat transfer is generally smaller, resulting in lower absolute thermal loss rates and reduced heat flux across the storage boundaries.

- Storage Sizing — Indicative Parameters

Sizing requirements are governed by the timescale and magnitude of the supply-demand imbalance to be buffered. The following indicative values are derived from analysis of district heating systems (Gadd & Werner, 2013) and are presented as order-of-magnitude references; actual sizing must be based on system-specific load profiles.

Table 4. Storage timescale

Storage Timescale	Indicative Volume (water, 40°C ΔT)	Governing Demand Pattern
Diurnal (daily)	~9 m³ / GWh annual delivery	Morning/evening demand peaks; hot water load
Weekly	Intermediate (weather-dependent)	Multi-day temperature swings; weather fronts
Seasonal (constant source)	>5,000 m³ / GWh annual delivery	Summer surplus to winter deficit transfer
Seasonal (solar thermal)	~12,000 m³ / GWh annual delivery	High seasonal mismatch; solar as sole source
Cooling (diurnal, ice or chilled water)	Varies with ΔT (8–12°C for water; high density for ice)	Daytime peak cooling demand; off-peak charging

Different Technologies

The following case studies cover the principal commercially deployed and emerging TES technologies, spanning both heating and cooling applications. Each technology is described in terms of its operating principle, applicable temperature range, key technical characteristics, cost parameters, and representative installations.

A. Sensible heat storage technologies

Water Accumulator (Cistern) Storage

Water accumulator cistern storage is the most widely deployed TES technology globally. A steel or reinforced concrete cistern contains stratified hot (or chilled) water, charged and discharged by displacing water between the supply and return sides of the connected energy network. The operating principle is identical for heating and cooling applications, with the thermal gradient inverted. Pressurised cisterns are designed to network operating pressure (typically 8–16 bar gauge), permitting supply temperatures above 100°C. They are often assembled from multiple factory-produced vessels in series. Atmospheric cisterns are site-built to bespoke designs, with maximum temperatures below 100°C but lower construction cost per unit volume, particularly at larger scales. For district cooling, atmospheric chilled water tanks operating at 4–12°C are common in urban energy centres and large commercial buildings. Form factor (height-to-diameter ratio) is a

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key design parameter governing stratification quality. Taller, more slender vessels maintain a sharper thermocline but incur higher structural costs. The most common ratio in Nordic heating installations is approximately 1:1.5 (width:height); chilled water cooling tanks often have a lower aspect ratio constrained by building integration requirements.

Applications

- ✓ District heating
- ✓ Solar thermal
- ✓ Industrial heat recovery
- ✓ District cooling (chilled water)

Representative installations

- Ptolemaida, Greece (pressurised district heating)
- Sunstone district cooling tank, Singapore (chilled water storage, 10,000 m^3)
- Solar district heating systems across Denmark (atmospheric tanks, 500–10,000 m^3)

Rock Cavern Storage

Rock cavern storage uses sealed underground excavations in competent bedrock as water-filled thermal reservoirs. The technology operates on the same displacement principle as cistern storage, but at very large scales unachievable with surface structures. The rock mass itself provides structural containment; watertight integrity requires either impermeable native rock or an applied liner. The typical operating temperature range extends to temperatures exceeding 100°C for water-column pressurized systems, whereas unlined cavern storage systems are generally limited to operating temperatures below 100°C.

Historically, the cost of purpose-blasting new caverns has been prohibitive. However, a significant number of decommissioned Cold War-era underground oil storage caverns in Sweden and Finland have been successfully converted to district heating storage at substantially lower cost. Converted caverns often have elongated horizontal geometries, which are thermally suboptimal compared to cubic or vertically oriented designs. Underground mine conversions have also been demonstrated, with examples in France.

Applications

- ✓ District heating
- ✓ Industrial heat storage
- ✓ Potential for large-scale district cooling

Representative installations

- Multiple converted oil cavern district heating storages in Sweden and Finland (operational since 2010s, volumes up to several hundred thousand m^3)
- Lyckebo cavern storage, Sweden (115,000 m^3, solar district heating, operational 1983)

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Aquifer Thermal Energy Storage (ATES)

Aquifer TES exploits natural water-bearing underground formations — typically sand, gravel, or permeable rock — to store and recover thermal energy via extraction and re-injection wells. At minimum one warm and one cold well are required. The permeable matrix retards the buoyancy-driven migration of the warm plume, providing natural thermal containment. ATES is one of the few storage technologies natively suited to combined heating and cooling: the cold side of a heating storage system is simultaneously a cold reservoir for cooling applications, and vice versa. The operating temperature range of this technology for heating applications typically lies between 45–85°C in shallow installations, while higher temperatures may be achieved in deep pressurized aquifer systems. On the other hand, for cooling applications, the technology generally operates within a cold-side temperature range of 6–16°C. ATES is particularly well established for commercial building combined heating and cooling in the Netherlands, Belgium, and Sweden, typically operating with heat pumps at near-ambient temperatures (15–25°C warm side, 5–12°C cold side). Higher-temperature district heating applications are less common but operational. Deep aquifers can in principle sustain temperatures above 100°C due to hydrostatic pressure, though buoyancy losses and chemical aggressiveness increase with temperature.

Examining ATES from a financial perspective, for heating applications with ~40°C temperature difference and output of 10–40 MW the total cost id approximately 100–150 €/kW installed capacity. For cooling systems (~10°C ΔT, 2–11 MW) is approximately 400–600 €/kW. Well construction accounts for approximately 50% of capital cost; piping and controls account for the remainder.

Applications

- ✓ District heating and cooling
- ✓ Building-level combined heating and cooling
- ✓ Industrial process cooling

Representative installations

- Neubrandenburg, Germany — Deep aquifer (1,200 m) coupled to a 77 MW CHP plant, with summer waste heat injection at 45°C and winter extraction at 75–85°C estimating 9 GWh capacity and 70% thermal recovery,
- Amsterdam, Netherlands — Extensive shallow ATES network serving combined heating and cooling for commercial buildings

Pit Thermal Energy Storage (PTES)

Pit thermal energy storage uses large excavated basins lined with HDPE membranes and filled with water, covered with an insulated floating lid to minimise surface heat loss. The primary technical limitation is the geometry. Pits have a wide, shallow form (width-to-depth ratio typically ~10:1), constrained by excavation stability angles (approximately 30°) and the depth of excavatable overburden. This geometry produces a less favourable surface-to-volume ratio than cisterns or caverns, increasing relative heat loss, and limits vertical stratification quality. Maximum temperature is capped at 100°C by the open water surface.

PTES is the lowest-cost large-scale seasonal storage technology currently commercially available, with benchmark construction costs of approximately 30–38 €/m³. The technology has been deployed extensively in Denmark in conjunction with solar district heating, with over 20 large-scale installations. Decommissioned

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open-cast mines and quarries present analogous storage opportunities with potentially lower excavation cost.

Applications

- ✓ Seasonal district heating
- ✓ Solar thermal integration
- ✓ Limited cooling applicability due to temperature constraints

Representative installations

- Dronninglund, Denmark (62,000 m³, seasonal solar heating, efficiency >90%)
- Marstal, Denmark (75,000 m³, Sunstore 4, combined solar/biomass/heat pump)

Borehole Thermal Energy Storage (BTES)

Borehole TES stores thermal energy in the solid bedrock through arrays of vertical boreholes, through which heat transfer fluid is circulated. Unlike water-based storage technologies, BTES does not maintain a spatial hot/cold separation; the rock temperature field is gradually modified across the entire field, with temperature declining progressively from the centre outward. Borehole arrays in series can partially improve the effective discharge temperature. BTES is widely used for building-scale combined heating and cooling with heat pumps, operating at near-ambient temperatures. Application at district heating supply temperatures is constrained by two factors. The first is the current temperature rating of commercially available borehole collectors (approximately 85°C continuous, while next-generation designs targeting 95°C and are in field trial). Second is the absence of a sharp thermocline, which means direct district heating supply is not feasible without heat pump boosting. For cooling applications, BTES functions as a cold store that accumulates winter cold for summer cooling, again typically with heat pump integration. In general, the temperature range is typically between 10–85°C (collector-limited), while near-ambient applications (10–30°C) are very common too.

Applications

- ✓ Combined heating and cooling for buildings and districts
- ✓ Solar seasonal storage
- ✓ Requires heat pump integration for district heating supply temperatures

Representative installations

- Drake Landing, Canada (144 boreholes, seasonal solar heating, ~97% solar fraction after 5-year charge-up)
- Brædstrup, Denmark (5 boreholes in series, solar heating, rock temperature 10–50°C)
- Emmaboda, Sweden (140 boreholes, waste heat from electric motor manufacturing)

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B. Phase Change Material (PCM) Thermal Storage

Phase Change Materials store thermal energy by exploiting the latent heat of a phase transition, most commonly the solid-to-liquid transition, rather than a temperature change. During charging, energy is absorbed by the PCM as it melts; during discharge, the same energy is released as the PCM re-solidifies. Because the phase transition occurs at or near a fixed temperature (the melting point), PCM storage inherently delivers energy at a near-constant temperature, unlike sensible heat stores which exhibit a declining (or rising, for cooling) outlet temperature as they discharge. This characteristic makes PCM well suited to applications requiring tight temperature control. PCMs exhibit a broad operational temperature range, spanning from approximately −30°C for cold storage and freezing applications to temperatures exceeding 300°C for industrial processes and concentrated solar power (CSP) systems. In building heating and cooling applications, the typical operating range is approximately 0–100°C, while most commercially deployed PCMs for HVAC systems operate efficiently between −10°C and 60°C, optimizing latent thermal energy storage and enhancing energy management under standard thermal comfort conditions.

PCM systems may be implemented through macro-encapsulation, micro-encapsulation, shape-stabilised composites, or slurry-based configurations, depending on the application scale and heat transfer requirements.

Applications

- ✓ Building heating and cooling
- ✓ District heating and cooling buffer storage
- ✓ Cold chain logistics
- ✓ Solar thermal
- ✓ Industrial process temperature control
- ✓ Demand response

In terms of latent heat storage density, PCMs significantly outperform conventional sensible heat storage materials under comparable operating temperature ranges. Their ability to absorb and release large quantities of energy during phase transitions enables compact thermal storage solutions with increased energy density. Water–ice systems, for instance, provide a latent heat of approximately 334 kJ/kg, whereas liquid water subjected to a 60°C temperature differential stores approximately 250 kJ/kg through sensible heat mechanisms. Organic PCMs such as paraffin waxes typically achieve latent heat capacities of 150–250 kJ/kg, while inorganic salt hydrates can reach 150–350 kJ/kg, often coupled with superior thermal conductivity characteristics that contribute to improved thermal response and system efficiency. The following table provides an overview of representative PCM categories and their corresponding thermophysical characteristics.

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Table 5. Representative PCM classes and their properties

PCM Class	Melting Point	Latent Heat	Thermal Conductivity	Typical Application
Water / Ice	0°C	334 kJ/kg	High (solid); Low (liquid)	Cooling storage, cold chain, ice TES
Paraffin waxes	18–70°C	150–250 kJ/kg	Low (~0.2 W/m·K)	HVAC, solar thermal, building integration
Fatty acids	20–65°C	150–210 kJ/kg	Low (~0.15 W/m·K)	Building wallboard, solar, HVAC
Inorganic salt hydrates	15–117°C	150–350 kJ/kg	Medium (~0.5 W/m·K)	District heating buffer, solar, building
Nitrate/chloride salts	120–550°C	100–200 kJ/kg	Medium–High	Industrial processes, CSP plants
Sugar alcohols (e.g. erythritol)	117–120°C	~340 kJ/kg	Medium	High-temp solar, industrial

PCM for Heating Applications

In district heating and building heating applications, PCMs with phase transition (melting points) temperatures in the range of 45–90°C are of particular interest due to their suitability for medium-temperature thermal energy storage systems. Among the most extensively investigated materials are salt hydrates (e.g., sodium acetate trihydrate, with a melting temperature of approximately 58°C) and selected paraffin-based compounds, owing to their favorable thermophysical characteristics and latent heat storage capacities. PCM-based thermal storage systems represent a compact alternative or complementary solution to conventional water-based thermal storage tanks, particularly in applications where space availability is limited, such as building-integrated energy systems. In district heating networks, PCM-integrated buffer storage units have demonstrated considerable potential for peak-load management and load shifting at the building substation level. By mitigating short-term thermal demand peaks, these systems can reduce peak mass flow requirements and potentially enable the downsizing of district heating network infrastructure, including pipeline dimensions and pumping capacity.

Despite these advantages, technical challenges remain associated with PCM implementation in heating applications. One of the most significant limitations is the enhancement of thermal conductivity, particularly for organic PCMs, which typically exhibit low thermal conductivity values (approximately 0.2 W/m·K). This characteristic results in relatively slow charging and discharging rates unless heat transfer enhancement techniques are incorporated, such as integration with high-conductivity structures or matrices, including metal fins, graphite foams, or encapsulated conductive composites. Although salt hydrates generally exhibit higher thermal conductivity compared to organic alternatives, they may suffer from operational issues such as phase segregation and supercooling during repeated thermal cycling, which can progressively reduce the effective latent heat storage capacity and long-term system performance.

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PCM for Cooling Applications

For cooling storage applications, ice-based storage systems (water undergoing phase transition at 0°C) represent the most widely implemented PCM technology. Ice offers one of the highest latent heat storage capacities among practical phase change materials, with a latent heat of fusion of approximately 334 kJ/kg, while also benefiting from well-established and predictable charging (ice formation) and discharging (melting) mechanisms. Ice thermal storage systems are commonly charged during off-peak periods by operating chillers under more favourable conditions characterized by higher efficiency and lower electricity tariffs. The stored cooling capacity is subsequently discharged during peak daytime periods to satisfy cooling demand. Owing to their technological maturity and operational reliability, ice-based TES systems constitute one of the most commercially established forms of PCM-integrated thermal storage and have been extensively deployed in commercial buildings, district cooling networks and industrial facilities worldwide.

For applications requiring cooling at temperatures above the freezing point, such as chilled water systems operating within the range of 6–12°C, phase change materials with melting temperatures between 6°C and 15°C become particularly relevant. Suitable materials include selected salt hydrates, hydrated inorganic salts, and eutectic mixtures, specifically engineered to achieve phase transitions within the desired temperature range. These materials facilitate the implementation of free-cooling strategies, whereby naturally available cooling sources—such as night-time ambient air, seawater, or groundwater—can be utilized and stored for subsequent daytime cooling demand, thereby reducing or potentially eliminating the reliance on conventional mechanical refrigeration systems.

Representative installations

- Frito-Lay distribution centre, USA (ice TES, 8,000 ton-hours capacity, peak demand reduction >50%)
- Tokyo Gas Building, Japan (ice storage integrated with district cooling)
- District cooling plants in the Middle East (ice and chilled water TES for peak demand management in extreme climates)

Limitations and Technology Readiness

Although PCM-based thermal energy storage technology has reached a high level of commercial maturity in specific applications—most notably ice storage systems and building-integrated PCM solutions—its deployment in large-scale district heating applications remains primarily at the pilot and demonstration stage. The large-scale implementation of PCM storage systems is currently constrained by several technical and economic challenges. These include the high material cost per unit of stored energy (kWh) relative to conventional water-based sensible heat storage systems, concerns regarding long-term cycling stability, and limitations associated with heat transfer performance. Repeated thermal cycling may induce degradation phenomena such as phase segregation and supercooling in salt hydrates, as well as volumetric expansion and structural deformation in paraffin-based materials, leading to reduced storage effectiveness over time. Furthermore, the inherently low thermal conductivity of many PCM materials necessitates the incorporation of heat transfer enhancement strategies—such as conductive matrices, fins, or encapsulation techniques—which increase both system complexity and overall cost. In addition, operational experience with non-ice PCM technologies at the multi-MWh scale remains limited, creating uncertainty regarding long-term reliability and large-scale integration performance.

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With specific regard to district heating systems, advanced salt-based thermal energy storage technologies, including latent heat storage systems utilizing PCMs and thermochemical energy storage concepts based on reversible chemical reactions, have not yet achieved commercial viability at the scale required for district heating network applications. Nevertheless, these technologies continue to represent an active and strategically important field of research and development due to their potential for achieving substantially higher energy storage densities and improved long-term thermal storage capabilities compared to conventional sensible heat storage approaches.

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4 Specific Technology

As previously stated, this series of Deliverables is directly associated with the implementation of the pilot application in Ptolemaida, involving the installation and operation of a 1 MW solar thermal park. Within this framework, the technology selected for deployment, testing and performance evaluation is the High-Vacuum Flat Plate (HVFP) solar thermal collector. The selection of this technology is primarily driven by its enhanced thermal insulation characteristics, high conversion efficiency, and suitability for medium- and high-temperature applications. A typical structure of an HVFP collector is presented in the following figure.

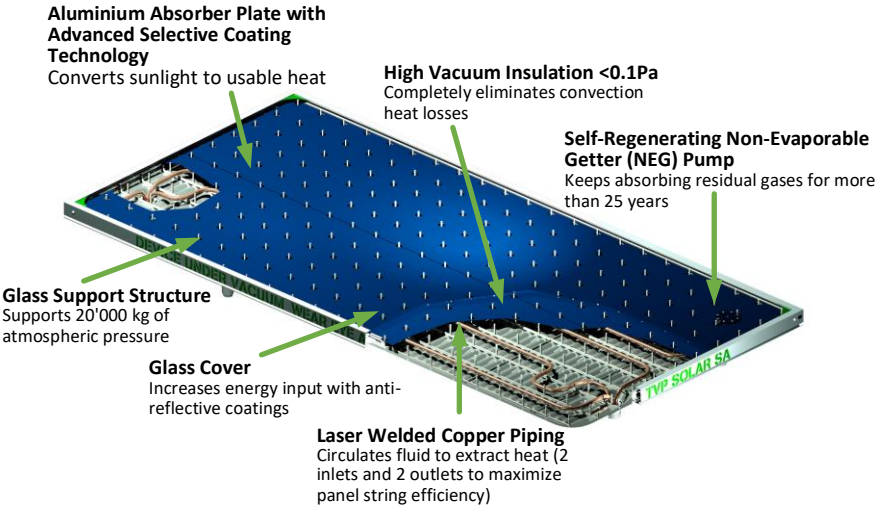


Figure 1. Structure of a HVFP solar collector

The high-vacuum technology incorporated into the MT-Power collector elements to be installed at the pilot site represents an advanced and innovative solar thermal solution. The technology is certified according to Solar Keymark standards and is capable of producing hot water and steam at temperatures up to 200°C, thereby offering a fully renewable and zero-emission alternative for industrial and district-scale heat generation applications. HVFP collectors are specifically engineered to maintain high thermal efficiency under a wide range of climatic conditions, including locations characterized by elevated diffuse solar radiation and moderate to low direct irradiance levels. This technological approach overcomes many of the operational limitations commonly encountered in conventional flat-plate collectors and evacuated tube solar systems. In particular, it extends the operational temperature range while maintaining high performance and year-round energy production capability for applications requiring operating temperatures above 80°C. Under standard full-sun operating conditions (1000 W/m² solar irradiance), the HVFP technology demonstrates a thermal energy conversion efficiency of approximately 65% at 80°C and 45% at 180°C. Even under moderate daytime radiation conditions (500 W/m²), the technology maintains high performance, achieving approximately 60% efficiency at 80°C and 40% efficiency at 130°C. These performance characteristics highlight the capability of the technology to operate efficiently even under suboptimal irradiation conditions. The following figure presents a comparative analysis between MT-Power HVFP technology and other commercially available solar thermal technologies.

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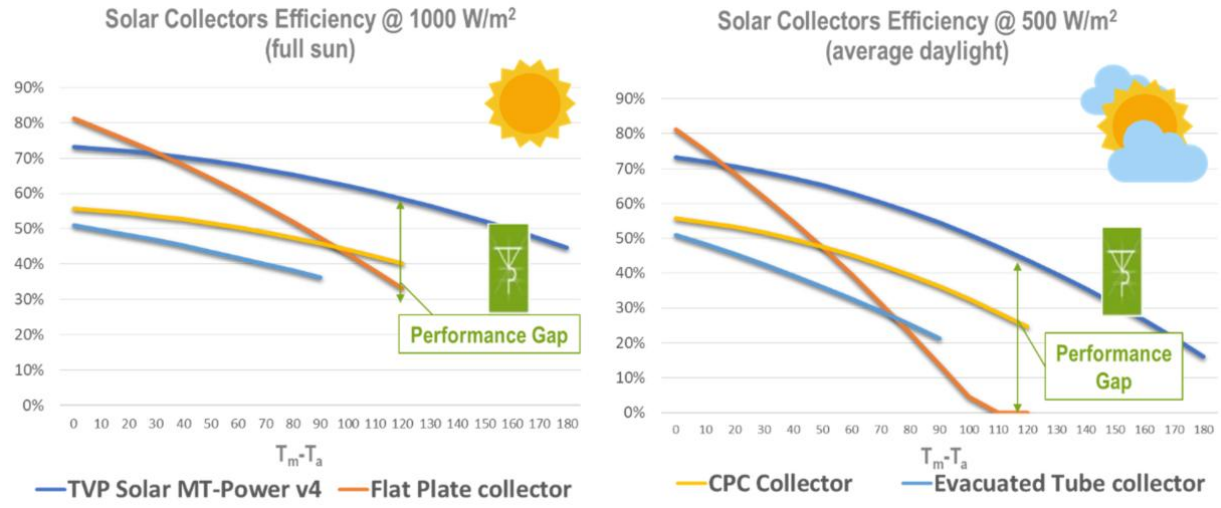


Figure 2. Comparative analysis between MT-Power HVFP technology and other commercially available solar thermal technologies

The operation of HVFP-based solar thermal systems is fully automated and controlled through an integrated monitoring and supervisory control architecture. System operation is managed by a Programmable Logic Controller (PLC) that dynamically activates different operational modes according to real-time measurements of solar irradiance and thermal conditions within the solar hydraulic circuit.

The principal operating modes are summarized below:

Preheated mode

This operational mode is initiated during morning startup conditions once predefined activation criteria are satisfied. Typical conditions may include solar irradiance levels exceeding 200 W/m² for a continuous duration greater than 300 seconds, within the available daylight operating window between sunrise and sunset. Target temperatures and circulation pump operating frequencies are configured by the system operator. Once the predefined thermal threshold is achieved, the system automatically transitions to the next operational phase.

Application Mode (Heat Delivery Mode)

During this operating state, the thermal transfer fluid is directed through the heat exchanger to deliver useful thermal energy to downstream applications. The flow rate is continuously regulated through a control algorithm that optimizes pump speed based on solar irradiance measurements obtained via a pyranometer. If operating conditions no longer satisfy the energy supply criteria, heat transfer to the secondary consumption circuit is interrupted, and the system reverts to reheating mode until design temperatures are re-established.

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Dry Cooling Mode

This safety-oriented operational mode is activated whenever system temperatures exceed predefined maximum allowable values. Under such conditions, a water-to-air heat exchanger (dry cooler) is engaged to dissipate excess thermal energy to the surrounding environment, preventing overheating and protecting system components from thermal stress or operational instability.

Defrost / Freeze Protection Mode

This operational state is designed to prevent freezing of the heat transfer medium within the solar hydraulic circuit. During nighttime operation or periods of low solar radiation (Radiation < 200 W/m²), if system temperatures approach predefined low-temperature thresholds (typically near 0°C), the solar field circulation pump is activated to induce fluid movement and prevent localized freezing conditions. Once temperatures increase above the critical threshold, circulation is discontinued. Where necessary, auxiliary heating may be employed to maintain minimum operating temperatures. Alternatively, antifreeze solutions such as glycol mixtures may be used within the primary solar loop.

System Shutdown Mode

The system automatically enters shutdown mode during periods without solar availability, typically between sunset and sunrise, minimizing parasitic energy consumption and preserving operational efficiency.

Compared to concentrating solar thermal technologies, HVFP systems provide several important advantages, including lower capital expenditures (CAPEX), reduced operational and maintenance costs (OPEX), simplified installation requirements, and improved operational suitability for climatic conditions characterized by medium to low annual solar radiation levels. These characteristics make HVFP technology particularly suitable for a broad range of industrial and district-scale thermal applications requiring low- to medium-temperature process heat, currently within an operating range of approximately 80°C–180°C. Consequently, the technology presents significant potential as a scalable solution for sustainable thermal energy production and integration into future renewable energy infrastructures.

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5 Conclusions

The first of the three Deliverables dedicated to solar thermal technology was developed with the objective of establishing the theoretical foundation and providing a comprehensive understanding of the technology, thereby creating the necessary background for the subsequent Deliverables in the series. These future Deliverables will focus on more specialized technical aspects, detailed engineering considerations and operational analyses, while simultaneously strengthening the connection with the pilot implementation in the Ptolemaida region involving the installation and operation of a 1 MW solar thermal park.

Within the scope of this Deliverable, the contribution of solar thermal technologies to thermal energy production for heating applications was analysed in detail. This functionality represents one of the most mature and widely adopted applications of solar thermal systems, as evidenced by the extensive number of existing use cases and large-scale implementations documented internationally. Subsequently, the Deliverable expands the discussion toward a less conventional yet highly promising application area through the introduction of solar cooling technologies. Particular attention is given to the mechanisms through which solar-derived thermal energy can be utilized to satisfy cooling demands, as well as to the technical parameters and operational conditions that must be considered for effective system implementation. This approach introduces a more integrated and holistic perspective regarding solar thermal energy utilization, particularly during summer periods when heating demand is significantly reduced or absent. An equally critical aspect addressed within the Deliverable concerns thermal energy storage, which constitutes a key enabling component for maximizing the effectiveness and flexibility of solar thermal systems. Given the potentially significant quantities of thermal energy generated, storage solutions become essential for mitigating temporal mismatches between energy production and demand. Various thermal storage approaches are presented and evaluated, primarily focusing on heat storage in the form of hot water. The analysis includes both mature and widely implemented technologies, such as conventional hot-water storage tanks, as well as more innovative alternatives including PCM technologies.

Finally, the Deliverable establishes a direct connection with the pilot application through the detailed presentation of the technology selected for field deployment, namely the HVFP solar thermal collector. The analysis of this technology defines the technical framework for the on-site implementation and serves as a transitional element toward the next Deliverables in the series. These subsequent reports will provide a more detailed description of the installed system while focusing on monitoring activities, operational performance assessment and the evaluation of the technology under real operating conditions.

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Annexes

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