TECHNOLOGY AND DEMONSTRATORS

Technical Report Subtask C – Part C1

C1: Classification and benchmarking of solar thermal systems in urban environments

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Gleisdorf, 15th June 2016 (revised version v1.1)

IEA Solar Heating and Cooling Programme

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

"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.

The member countries of the Programme collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 53 such projects have been initiated to-date, 39 of which have been completed. Research topics include:

- ⚹ Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44)
- ⚹ Solar Cooling (Tasks 25, 38, 48, 53)
- ⚹ Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- ⚹ Solar District Heating (Tasks 7, 45)
- ⚹ Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52)
- ⚹ Solar Thermal & PV (Tasks 16, 35)
- ⚹ Daylighting/Lighting (Tasks 21, 31, 50)
- ⚹ Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- ⚹ Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43)
- ⚹ Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- ⚹ Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

- ➢ SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- ➢ Solar Heat Worldwide – annual statistics publication
- ➢ Memorandum of Understanding – working agreement with solar thermal trade organizations
- ➢ Workshops and conferences

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Content

1 Scope and content of Subtask C

In the framework of IEA-SHC Task 52 the future role of solar thermal in urban energy systems is investigated. In Subtask C "*Technology and Demonstrators*" an overview and analysis over corresponding state-of-the-art applications is given.

In Report *C1: Classification and benchmarking*, solar thermal system configurations suitable for applications in urban environments are identified and characterized by representative techno-economic benchmark figures from a set of best practice examples. Objective is to provide a comprehensive data base for techno-economic (pre-) evaluations, especially applicable for urban planners / energy system planners without deeper theoretical solar thermal expertise.

In Report *C2: Analysis of best practice examples*, information about built best practice examples as well as conceptual feasibility studies of solar thermal applications in urban environments is summarized. Objective is to highlight technical potentials, innovative approaches and restrictions of solar thermal applications in urban environments in a holistic energy system context on the one hand and to identify and describe lessons learned regarding applied methodologies, success factors and barriers on the other side.

In addition, a *Best-practice Leaflet* provides flash light information and impressions about seven best practice examples from Austria, Denmark, Germany, Sweden and Switzerland. The examples represent the entire range of solar thermal system configurations suitable for applications in urban environments including systems, which are hydraulically connected to a district or block heating grid, as well as systems which are directly attached to individual buildings.

2 Methodology

Classification and benchmarking of solar thermal systems in urban environments presented in this report is derived from techno-economic analyses of 46 solar thermal systems in operation from Austria, Denmark and Germany.

2.1 Boundaries for the assessment of technical and economical parameters

All technical and economical parameters of the investigated solar thermal systems are elaborated for both solar loop and solar energy storage. Conventional heat supply is not considered (cf. Figure 1).
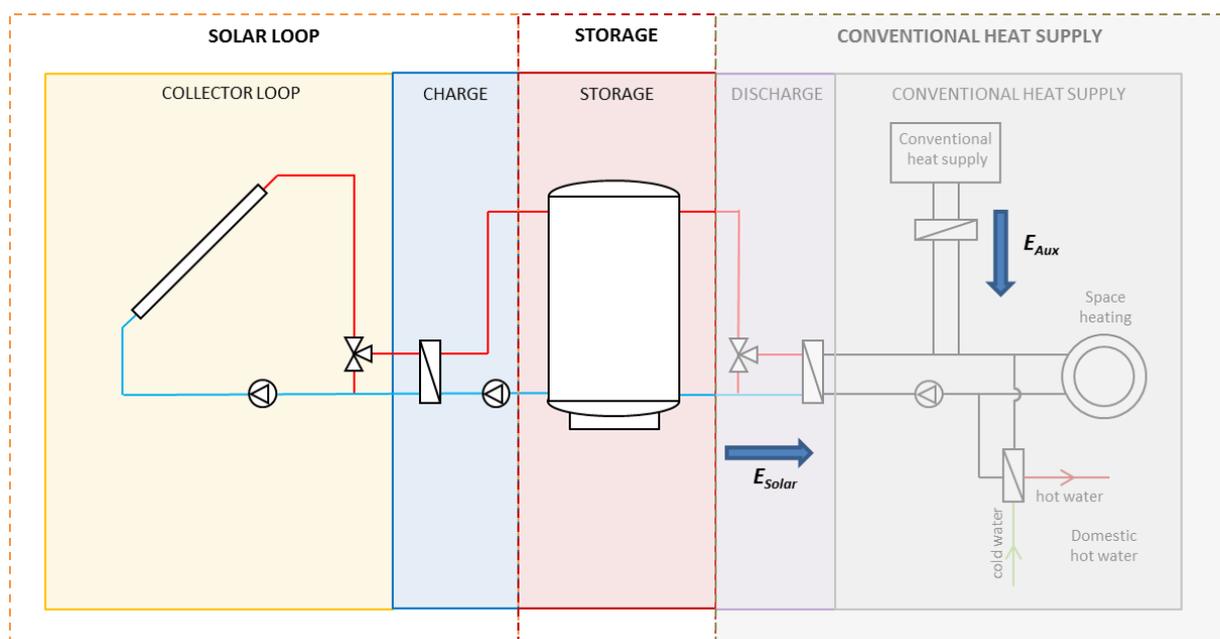
Figure 1: System boundaries for the solar thermal systems investigated

All specific benchmark figures presented in chapter 4 are referred to gross collector area installed (e.g. €/m²$_{gross}$, kWh/m²$_{gross}$). Cost data refer to end-user (customer) prices excluding value added taxes or subsidies. Solar energy yield *SE* is referred to as *specific* annual *useful* thermal energy delivered by the solar thermal system in kWh per m² gross collector area installed (thermal losses in solar loop piping and thermal energy storage considered). Solar fraction *sf* is defined as share of annual *useful* solar thermal supply E_{Solar} to total thermal energy supply (E_{Solar} + E_{Aux}).

$$sf = \frac{E_{Solar}}{(E_{Solar} + E_{Aux})} \qquad \text{Eq. 1}$$

2.2   Method for the assessment of the economic performance

The economic performance of the investigated solar thermal systems is quantified using the levelized cost of energy (*LCOE*) approach (e.g. acc. to /1/).

The idea of this approach is to compare the total costs (*C*) related to an energy supply system with the resulting energy supplied by this system (*E*). Since both the costs as well as the energy supplied are subject to the time preference of the investors, both terms are discounted at the interest rate *r* with an economic assessment period of *t*. *LCOE* are calculated according to Eq. 2 next:

$$LCOE = \frac{\sum_{t=1}^{t_{ges}} C_t \cdot (1+r)^{-t}}{\sum_{t=1}^{t_{ges}} E_t \cdot (1+r)^{-t}} \qquad \text{Eq. 2}$$

The calculation of levelized cost of solar thermal generated heat $LCOE_{ST}$ in this report is derived from Eq. 2 and may be expressed as following:

$$LCOE_{ST} = \frac{I_0 + \sum_{t=1}^{t_{ges}} A_t \cdot (1+r)^{-t}}{\sum_{t=1}^{t_{ges}} SE \cdot (1+r)^{-t}} \qquad \text{Eq. 3}$$

$LCOE_{ST}$	levelized cost of solar thermal generated heat [€/kWh]
I_0	specific solar thermal system costs incl. installation (excl. VAT and subsidies) [€/m²$_{gross}$]
A_t	fixed and variable O&M expenditures in the year *t* [€/m²$_{gross}$]
SE	solar energy yield in the year *t* [kWh/m²$_{gross}$]
r	discount (interest) rate [%]
t_{ges}	period of use (solar thermal system life time in years) [a]
t	year within the period of use (1,2,… t$_{ges}$)

3   Classification - Solar thermal systems in urban environments

From a technical point of view a large variety of different concepts for the (hydraulic) integration of solar thermal systems in urban environments exist. Basically, one may distinguish between solar thermal systems which are directly attached to individual buildings (residential or non-residential buildings) and solar thermal systems which are hydraulically connected to a thermal grid (block heating or district heating grid) for the supply of multiple buildings [1].

Based on these two categories, Table 1 provides a classification for the most commonly applied solar thermal system concepts suitable for urban applications.

Table 1: Classification matrix for solar thermal systems in urban environments

Solar assisted heating of individual buildings	
A1) Solar domestic hot water systems in single family homes (DHW-SFH) A2) Solar-combi systems in single family homes (CS-SFH) A3) Solar-combi systems in multi-family homes (CS-MFH)	
	Residential buildings (single family homes, multi-family homes, apartment blocks, etc.) **Non-residential buildings** (schools, hospitals, hotels, office buildings, production halls, etc.)
Solar assisted heating of multiple buildings via thermal grid	
B1) Solar assisted district heating (SDH) B2) Solar assisted heating of building blocks and urban quarters (SBH)	
	Case A: <u>central</u> storage + <u>central</u> solar thermal collector field (central solar feed-in)
	Case B: <u>central</u> storage + <u>distributed</u> solar thermal collector field (distributed solar feed-in; solar supply to heating grid only)
	Case C: <u>distributed</u> storage + <u>distributed</u> solar thermal collector field (bi-directional feed-in or solar supply to building only)
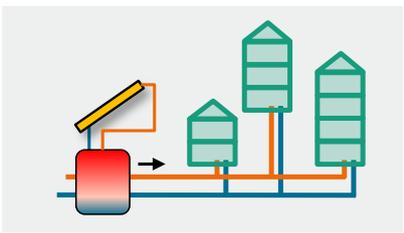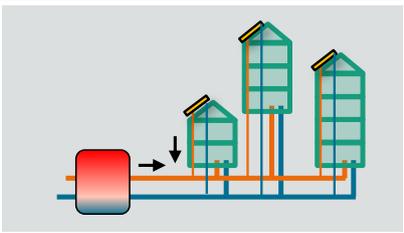
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[1] According to **/2/** a **thermal grid** can be defined as a network of pipes connecting buildings in a neighbourhood, city quarter or whole city, so that they can be served from centralised and/or distributed thermal energy supply technologies (such as boilers, CHP plants, solar thermal systems, heat pumps, waste heat from industry, etc.). Depending on the size of the pipe network it can be distinguished between district heating grids (large pipe networks for the supply of communities up to whole cities) and block heating grids (smaller pipe networks for the supply of multiple buildings in a neighbourhood).

3.1   Solar assisted heating of individual buildings

Solar assisted heating of residential and non-residential buildings (e.g. single and multi-family houses, terraced houses, apartment blocks, hotels, schools, hospitals, production halls, etc.) is commonly applied in countries all over the world [2].

Characteristic state of the art applications are building integrated (on-roof, in-roof) and supply thermal energy directly to the building's heating network for either domestic hot water or both domestic hot water and space heating (the latter are referred to as "*solar combi-systems*"). Usually, this kind of solar thermal applications are part of bivalent or multivalent [3] building heating and cooling systems including a thermal (diurnal) storage.

In Table 2 examples for solar thermal systems in single and multi-family homes are shown.

Table 2: Examples for solar thermal systems in single and multi-family homes [picture source: AEE INTEC]

A1) Solar domestic hot water systems in single family homes **DHW-SFH**	
A2) Solar-combi systems in single family homes **CS-SFH**	
A3) Solar-combi systems in multi-family homes (terraced houses, apartment blocks) **CS-MFH**	

Solar domestic hot water systems in single family homes (DHW-SFH) are usually designed to provide 65 to 75% of the annual domestic hot water demand. In summer (May to August) usually 100% of the thermal energy needs for domestic hot water are supplied by this kind of solar thermal

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[2] In Central and North Europe, North America and Australia the majority of solar thermal systems attached to individual buildings are pumped systems (closed loops with forced circulation) equipped with flat plate collectors. By contrast, in Southern Europe, Latin America, the MENA region and Africa thermosiphon systems especially for small scale domestic hot water applications are dominating. In China, by far the largest solar thermal market world-wide, thermosiphon systems equipped with evacuated tube collectors are predominant **/3/**. In this report only pumped solar thermal applications with flat plate collectors have been investigated.

[3] In the residential sector, solar thermal systems typically provide 65-75% of the annual domestic hot water demand or 15-35% of the annual building heating demand (domestic hot water + space heating). The missing demand hence needs to be provided by one or more additional auxiliary energy conversion units (may be boilers, heat pumps, electrical heaters). Respective energy supply systems consisting of two or more heat sources are referred to as "*bivalent*" or "*multivalent*" energy supply systems.

systems. In order to utilize the energy from the sun most efficiently these systems are equipped with a domestic hot water tank with a storage volume equivalent to around double the domestic hot water demand for one day. Further information (design guidelines, technical standards, etc.) regarding solar domestic hot water systems in single family homes can be found here: /4/, /5/.

Solar-combi systems in single family homes (CS-SFH) and **Solar-combi systems in multi-family homes (CS-MFH)** are usually designed to provide 15 to 35% of the buildings annual heating demand (domestic hot water + space heating). Similar to the solar domestic hot water systems, solar energy storage is needed for the efficient utilization of the energy gains from the solar thermal system. The design of Solar-combi systems is sensitive to the building standard resp. the annual space heating demand, the conventional heating system of the building (e.g. low temperature floor heating or higher temperature radiator heating) and the domestic hot water demand pattern. Further information (design guidelines, technical standards, etc.) regarding solar-combi systems in single and multi-family homes can be found here: /6/, /7/, /8/.

3.2   Solar assisted heating of multiple buildings via thermal grid

In dense urban areas multiple buildings up to whole cities may be attached to block or district heating grids. Compared to heating of single buildings, thermal grids provide several advantages such as the spatial separation of thermal energy conversion and thermal energy demand, the utilization of various heat sources within one connected system or the utilization of waste heat from combined heat and power (CHP) plants and/or industry.

Solar thermal systems connected to thermal grids have been applied in Europe since the early 1980's. Most notably in Scandinavia (Sweden, Denmark) but also in Austria, Germany, Spain and Greece a number of large-scale applications >350 kW_{th} (500 m²) exist [4]. In sum, 219 large-scale solar thermal systems connected to heating grids and 17 systems connected to cooling grids were in operation in Europe by October 2015. The total installed capacity of these systems equals 694 MW_{th} (991,000 m²) [5].However, compared to the cumulated installed solar thermal capacity in Europe these large-scale applications only cover a small niche segment with a market share of around 2 % [6].

Denmark is the only country world-wide, where a commercial market for large-scale solar thermal plants connected to thermal grids could establish. By October 2015, seventy solar district heating plants with a total installed capacity of 531 MW_{th} (759,000 m²) were in operation (more than ¾ of the total installed capacity in Europe). Average system size calculates to 7.6 MW_{th} (10,850 m²).

In several other European countries smaller niche markets exist, such as in Austria where 25 systems >350 kW_{th} (500 m²) connected to urban district heating grids, community-based biomass heating grids or block heating grids are installed. In Germany, several remarkable demonstration plants for the solar assisted heating of building blocks and urban quarters with seasonal storage were built. Also from other European countries such as Sweden (22 plants), Spain (16 plants), Greece, France, Poland (14 plants each) and Switzerland (9 plants) interesting achievements are reported (Figure 2).

Large-scale solar thermal plants connected to thermal grids
European markets - capacities installed and No. of systems by country

	DK*	DE	AT	SE	other	PL	NL	GR	FR	ES	CH	IT
Capacity [MWth]	531	30	27	22	16	15	11	11	10	9	6	4
No. of systems [-]	70	25	25	22	12	14	8	14	14	16	9	7
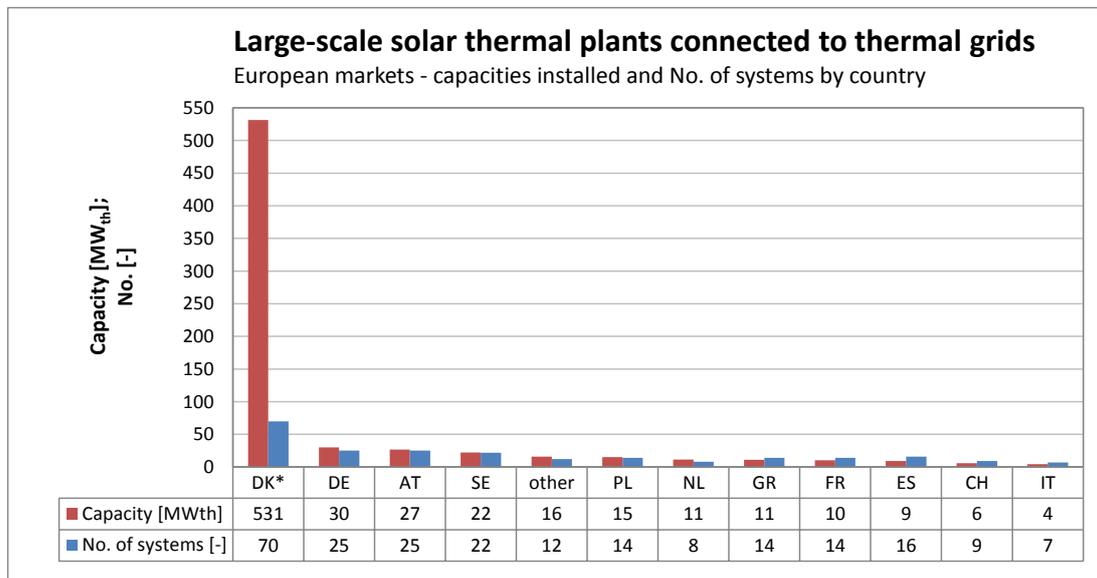
Figure 2: Large-scale solar thermal plants connected to thermal grids in Europe – capacities installed and No. of systems by end of 2014 (*Denmark: October 2015) *(Data source: Dalenbäck J.-O. - Chalmers University of Technology, SE and Trier D. – PlanEnergi, DK)*

In Table 3 examples for solar thermal systems connected to district or block heating grids are shown.

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[4] Apart from Europe, very few large-scale solar assisted heating and cooling grids are documented. Two best practice examples from e.g. Canada and Saudi Arabia are described in **/9/** and **/10/** respectively.

[5] Calculation AEE INTEC based on data from Jan-Olof Dalenbäck - Chalmers University of Technology, SE and Daniel Trier – PlanEnergi, DK

[6] Calculation AEE INTEC based on data from ESTIF, 2015 **/11/**

Table 3: Examples for solar thermal systems connected to thermal grids (district heating and block heating grids)

Solar district heating (SDH)
- <u>central solar feed-in</u>
- ground mounted collectors
- <u>seasonal storage</u>
- country: DK

*PTES: pit thermal energy storage

Location: Vojens, DK
Commissioning: 2012/2015 (extended)
Collector field size: 70,000 m²
Storage: seasonal (200,000m³ PTES*)
Solar fraction: 45-50%
Picture source: Vojens Fjernvarme

Location: Dronninglund, DK
Commissioning: 2014
Collector field size: 37,600 m²
Storage: seasonal (62,000m³ PTES*)
Solar fraction: 50%
Picture source: Dronninglund Fjernvarme

Solar district heating (SDH)
- <u>central solar feed-in</u>
- ground/roof mounted collectors
- <u>diurnal storage</u>
- countries: DK, AT, DE

*TTES: tank thermal energy storage

Location: Saeby, DK
Commissioning: 2011
Collector field size: 11,866 m²
Storage: day (existing 2x2700 m³ TTES*)
Solar fraction: 6%
Picture source: Sæby Varmeværk

Location: Eibiswald, AT
Commissioning: 1997/2013 (extended)
Collector field size: 2,450 m²
Storage: day (175 m³ TTES*)
Solar fraction: 13%
Picture source: S.O.L.I.D. GmbH

Solar district heating (SDH)
- <u>distributed solar feed-in</u>
- ground/roof mounted collectors
- no storage/diurnal storage
- country: AT

*no storage needed due to low solar fraction; district heating (DH) grid acts as buffer

Location: Graz, AT
Commissioning: 2007/2015 (extended)
Collector field size: 7,450 m²
Storage: no storage (DH grid*)
Solar fraction: < 1 %
Picture source: S.O.L.I.D. GmbH

Location: Wels, AT
Commissioning: 2011
Collector field size: 3,400 m²
Storage: no storage (DH grid*)
Solar fraction: 1 %
Picture source: MEA Solar GmbH

Solar block heating (SBH)
- roof/(ground) mounted collectors
- day/week/seasonal storage
- countries: AT, DE

*TTES: tank thermal energy storage

Location: Salzburg; AT
Commissioning: 2011/2013 (extended)
Collector field size: 2,050 m²
Storage: day/week (200 m³ TTES*)
Solar fraction: 25%

Location: Munich, DE
Commissioning: 2007
Collector field size: 2,800 m²
Storage: seasonal (5,700 m³ TTES*)
Solar fraction: 46%

Picture source: Salzburg AG   Picture source: ZAE Bayern

Solar thermal systems connected to district heating grids (SDH – solar district heating)

With district heating communities up to whole cities are supplied with thermal energy by means of a district heating grid. Solar-thermal feed-in may be centralized (close to the boiler house/district heating plant -Figure 3, No. 1a/1b) or distributed (at any point of the district heating grid -Figure 3, No. 2a/2b). Depending on space availability installation of the collectors may be possible on ground (Figure 3, No. 1a/2a) or building integrated (Figure 3, No. 1b/2b). Distributed and building integrated solar thermal plants may be hydraulically designed in a way to either supply the district heating grid only (Figure 3, 2b'), to supply the building only (district heating as back-up – Figure 3, 2b'') or to supply both the building and the district heating grid (bi-directional feed-in – Figure 3, 2b''').

Basically, SDH plants may be technically realized without any additional solar energy storage if the solar supply at the feed-in point is very low compared to the demand base load. However, in most cases solar energy storages are attached in close distance to the solar thermal feed-in point.

Solar fractions of best-practice solar assisted district heating installations range from very low (<1%-2%) for SDH plants without storage (e.g. several examples for distributed solar feed-in in district heating grids in Austria) up to 5-15% for SDH plants with short-term (diurnal) storages (e.g. most of the Danish SDH plants [7] as well as solar assisted biomass heating plants in Austria and Germany [8]). Higher solar fraction of 45-55% can be reached if seasonal storages are installed [9].

1a: central feed-in, ground mounted	2a: distributed feed-in, ground mounted
1b: central feed-in, roof mounted	2b': distributed feed-in, roof-mounted, *solar supply to heating grid only*
	2b'': distributed feed-in, roof-mounted, *solar supply to building only*
	2b''': distributed feed-in, roof-mounted, *bi-directional feed-in*
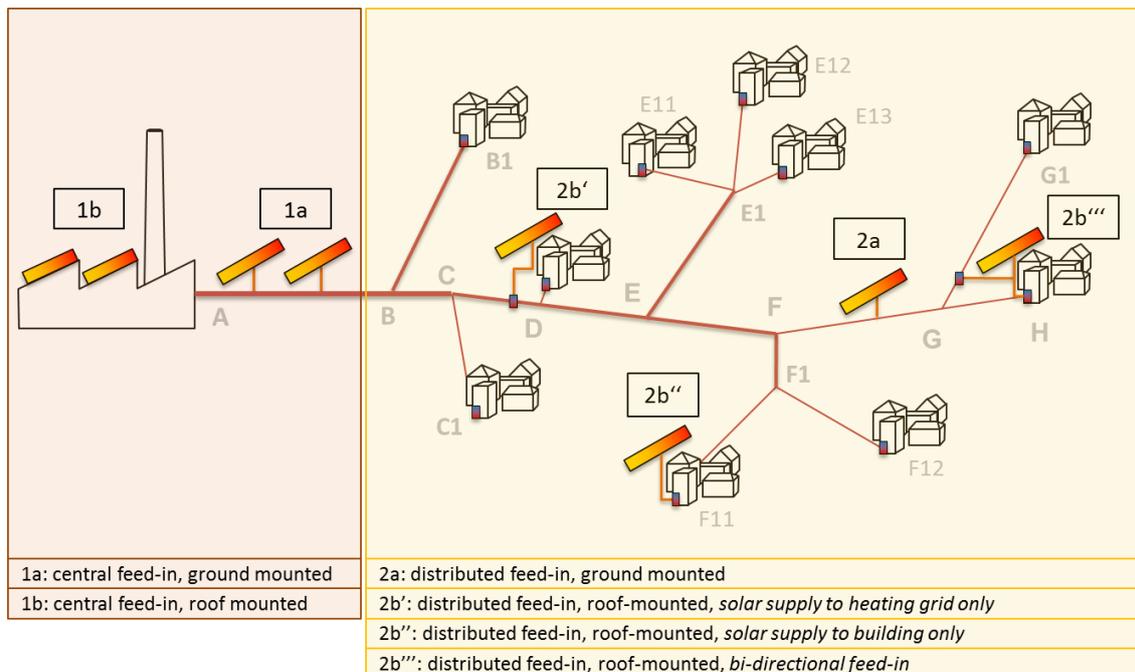
Figure 3: Integration options for solar thermal systems in district heating grids (source: AEE INTEC adapted from /12/)

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[7] Most of the Danish SDH installations are ground mounted flat plate collector fields hydraulically connected to (**usually already existing**) load-balancing storages in close distance to the district heating main distribution line (Figure 3, No. 1a). Typical solar fractions range from 5-15 % of the thermal energy demand for communities with 1,000 to 2,500 households.

[8] In Austria, Germany and Switzerland it is quite widespread to supply communities with district heat based from local biomass. In Austria, around 30 of such **local biomass heating grids** have been extended by solar thermal systems in order to cover the summer base load and to avoid part load operation of the biomass boiler(s) or biomass CHP plants installed (**solar assisted biomass heating plants**). Typically, the solar thermal collectors are mounted on the roof of the biomass (wood-chip) storage building.

[9] Three very large ground mounted SDH plants with central feed-in connected to pit thermal energy storages (PTES) have been realized in the Danish cities of Marstal (23.3 MWth; 33,300 m²; 85,000 m³) **/13/**, Dronninglund (26.3 MWth; 37,573 m²; 61,700 m³) **/14/** and Vojens (50 MWth, 70,000 m², 203,000 m³) **/15/**.

Further information (design guidelines, technical standards, etc. regarding solar district heating can be found here: **/16/**, **/17/**. A database of techno-economic benchmark figures and monitoring data of several Danish best practice examples can be accessed here: **/18/**.

Solar thermal systems connected to block heating grids (SBH – solar block heating)

With block heating multiple buildings in a neighborhood are jointly connected and supplied with thermal energy by means of a block heating grid. Solar thermal systems attached to block heating grids are typically building integrated and may supply thermal energy either directly to the building attached and/or to the thermal grid connected. Solar energy storages may be attached to the buildings (mostly diurnal storages) and/or to the heating network (can be diurnal, weekly or seasonal storages). Typical solar fractions of solar assisted block heating systems range from 10-20% for installations with diurnal storages and from 40-70% for installations with seasonal storages [10]. Solar fractions of > 90% have been successfully demonstrated [11].

Figure 4 schematically shows an urban district (Freiburg-Glutleutmatten, DE) supplied by a block heating grid and assisted by various distributed and roof-mounted solar thermal systems (orange areas). The hydraulic integration of the solar thermal systems as highlighted in the red box is same for all buildings.
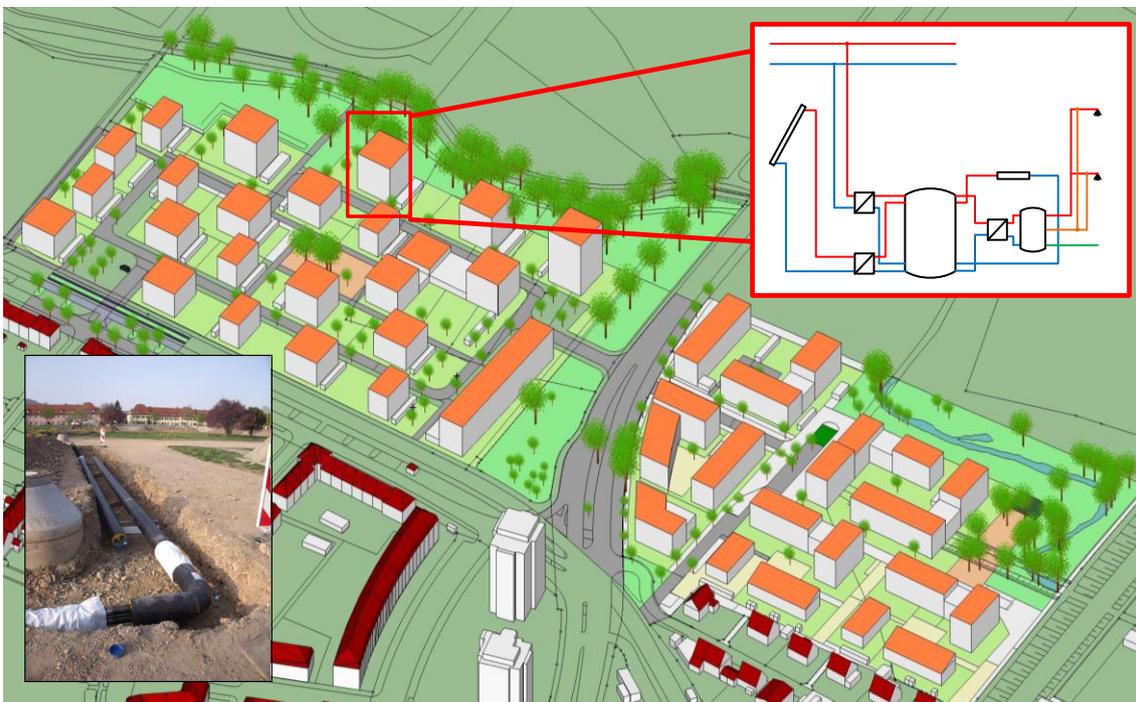
Figure 4: Schematic overview over the solar assisted block heating system in Freiburg- Glutleutmatten, DE (source: Fraunhofer ISE) (Details – based on design data: Total heated floor area: 40,000 m² / Total roof-mounted solar thermal system area: 2,000 m² / Total solar energy storage volume: 160 m³ / Total annual thermal energy demand: 2,200 MWh / Total annual solar energy yield: 660 MWh / Solar fraction: 20%)

Especially, block heating grids designed for the supply of new and renovated low-energy neighborhoods or urban quarters show good potential for the integration of solar thermal systems since lower supply temperatures are needed for space heating. Amongst others, in Task report *C2:*

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[10] In Germany, ten solar thermal systems with seasonal storage for the supply of several terraced houses up to small urban quarters have been demonstrated with different kinds of long-term storage technologies attached. Solar thermal system sizes range from 560 m²gross to around 8,200 m²gross and solar fractions achieved are between 45 and 75 %.

[11] Highest solar fractions in combination with seasonal storage of solar heat are achieved in Alberta, Canada where more than 90 % of the energy needed for space heating of 52 detached energy efficient homes are provided by a 1.6 MWth (2,293 m²) solar thermal plant connected to a borehole thermal energy storage (BTES) with an activated soil volume of 34,000 m³ (144 boreholes a 35 m depth) **/19/**.

Analysis of built best practice examples and conceptual feasibility studies, the example of the solar-assisted urban quarter Freiburg-Glutleutmatten is described, analyzed and discussed in more detail.

4   Benchmarks - Solar thermal systems in urban environments

The benchmarks presented in this chapter were derived from a set of best practice examples in operation from countries participating in IEA-SHC Task 52 (AT, DE, and DK). In sum, 46 systems covering all categories from Table 2 and Table 3 have been analyzed. Objective of chapter 4 is to provide a comprehensive data base for techno-economic (pre-) evaluations regarding the role of solar thermal in urban energy systems, especially applicable for urban planners / energy system planners without deeper theoretical solar thermal expertise. For each system investigated at least the following characteristics and key figures were determined:

Energy / technical data:

- Solar thermal system category (according to classification in Table 2 and Table 3)
- Kind of solar thermal collector
    - FPC – flat plate collector
    - ETC – evacuated tube collector
- Kind of solar energy storage
    - domestic hot water tank (DHW-tank)
    - pressurized tank thermal energy storage (pressurized TTES)
    - non-pressurized tank thermal energy storage (non-pressurized TTES)
    - BTES – borehole thermal energy storage (only seasonal storages)
    - PTES – pit thermal energy storage (only seasonal storages)
    - ATES – aquifer thermal energy storage (only seasonal storages)
- Size per unit in gross collector area [m^2_{gross}]
- Thermal peak capacity per unit [kW_{th}]
- Energy storage volume per unit [$ltr._{H2Oe}$]
- Annual *useful* solar energy supply per unit (*E_{Solar}*) [kWh/a]
- *Specific* energy storage volume per unit [$ltr._{H2Oe}/m^2_{gross}$]
- Typical *s*olar energy yield *SE* [$kWh/(m^2_{gross} \cdot a)$]
- Typical solar fraction *sf* [%]
- Typical technical solar thermal system life time [yrs.]

Financial data:

- *Specific* cost per unit **ready installed** (excl. VAT, excl. subsidies) [$1,000€/m^2_{gross}$]
- *Specific* cost per unit for **material only** (excl. VAT, excl. subsidies) [$1,000€/m^2_{gross}$]
    - Cost (material) solar loop (collectors, steel structures, piping, control)
    - Cost (material) storage (tank, insulation)
- Specific cost per unit for **labor only** (excl. VAT, excl. subsidies) [$1,000€/m^2_{gross}$]
    - Labor required per unit (design, tendering, mounting, commissioning) [hrs.]
    - Labor cost [€/hrs.] (excl. VAT)
- Fixed O&M cost per unit [€/a]
- Variable O&M per unit [€/a]

Levelized cost of solar thermal heat:

Based on the energy and financial data levelized cost of solar thermal heat (*$LCOH_{ST}$*) were calculated according to Eq. 3.

- *$LCOH_{ST}$* per unit **ready installed** (excl. VAT, excl. subsidies) [€-ct/kWh]

4.1   Summary of characteristic techno-economic benchmark figures

In the following tables characteristic technical and financial benchmark figures are summarized for

- A) solar thermal systems in single and multi-family homes (Table 4)
- B) <u>roof-mounted</u> solar thermal systems connected to (block) heating grids (Table 5) and
- C) <u>ground-mounted</u> solar thermal systems connected to (district) heating grids (Table 6)

Table 4: Benchmarks for solar thermal systems in single and multi-family homes (size of sample: 21)

Solar thermal system category	DHW-SFH Solar domestic hot water systems in single family homes	CS-SFH Solar-combi systems in single family homes	CS-MFH Solar-combi systems in multi-family homes
All systems of this category are **roof mounted** All systems of this category are equipped **with short-term (diurnal) storages**			
Energy/technical data			
Kind of solar thermal collector used *optional*	**FPC** *ETC*	**FPC** *ETC*	**FPC** *ETC*
Kind of solar energy storage used	**DHW-tank**	**TTES (pressurized)**	**TTES (pressurized)**
Typical size per unit [m²gross] *- range (from - to)*	**7** *5 – 10*	**18** *12 – 24*	**100** *30 – 300*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**5** *4 – 7*	**13** *8 – 17*	**70** *21 – 210*
Typical storage volume per unit [ltr.]	**400**	**1,500**	**9,000**
Typical annual production per unit [kWh/a]	**2,625**	**5,940**	**39,500**
Specific storage volume per unit [ltr./m²gross] *- range (from - to)*	**65** *50 - 80*	**85** *60 - 110*	**95** *70 - 120*
Typical solar energy yield *SE* [kWh/m²gross/a] *- range (from - to)*	**380** *330 - 430*	**330** *310 - 350*	**400** *350 - 450*
Typical solar fraction sf [-] *- range (from - to)*	**68%** *60 – 75%* (domestic hot water only)	**20%** *15 – 40%* (DHW + space heating)	**15%** *10 – 25%* (DHW + space heating)
Technical life time [years]	25	25	25
Financial data			
<u>Specific</u> cost <u>ready installed</u> [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.93** (+/- 13%) *(0.81 – 1.05)*	**0.76** (+/- 13%) *(0.67 – 0.86)*	**0.66** (+/- 21%) *(0.52 – 0.80)*
<u>Specific</u> cost (<u>material only</u>) [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.70** (+/- 6%) *(0.66 – 0.74)*	**0.61** (+/- 8%) *(0.57 – 0.66)*	**0.55** (+/- 20%) *(0.44 – 0.66)*
Labor required [hrs.] Labor cost [€/hr.] (excl. VAT)	18 (+/- 6hrs) 90 (reference: AT)	30 (+/- 10hrs) 90 (reference: AT)	120 (+/- 30hrs) 90 (reference: AT)
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**6.5** (+/-13%) *(5.7 – 7.3)*	**13.8** (+/-13%) *(12.0 – 15.5)*	**65.8** (+/-21%) *(52.1 – 79.5)*
Fixed O&M per unit [€/m²gross/a]*	7.0	6.1	5.5
Variable O&M per unit [€/m²gross/a]**	1.4	1.2	1.4

Levelized cost of heat *LCOH* [€-ct/kWh] *- range (from - to)*	**16.2** (+/- 12%) *(14.3 – 18.1)*	**15.5** (+/- 12%) *(13.7 – 17.4)*	**11.2** (+/- 20%) *(8.9 – 13.4)*

* 1% of net investment cost (excl. labor)

** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh

Table 5: Benchmarks for <u>roof-mounted</u> solar thermal systems connected to (block) heating grids (size of sample: 14)

Solar thermal system category	SBH: Solar block heating Solar assisted heating of building blocks and urban quarters (roof-mounted collector field)	
All systems of this category are **roof-mounted** and may be equipped with either - short-term (diurnal) storages **(A)** or - long-term (seasonal) storages **(B)**		
Energy/technical data	**A) with diurnal storage**	**B) with seasonal storage**
Kind of solar thermal collector used *optional*	**FPC** *ETC*	**FPC** *(ETC)*
Kind of solar energy storage used *optional*	**pressurized TTES** *non-pressurized TTES*	**BTES** *non-pressurized TTES, PTES, ATES*
Typical size per unit [m²gross] *- range (from - to)*	**1,000** *500 – 5,000*	**5,000** *1,000 – 10,000*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**700** *350 – 3,500*	**3,500** *700 – 7,000*
Typical storage volume per unit [m³.H2Oe]	**100**	**12,000**
Typical annual production per unit [MWh/a]	**390**	**1,500**
Specific storage volume per unit [ltr./m²gross] *- range (from - to)*	**100** *75 – 125*	**2,400** *1,400 – 3,400*
Typical solar energy yield *SE* [kWh/m²gross/a] *- range (from - to)*	**390** *350 - 450*	**300** *260 - 340*
Typical solar fraction sf [-] *- range (from - to)*	**20%** *10 – 25%*	**50%** *40 – 75% (up to 90%)*
Technical life time [years]	25	25
Financial data	**A) with diurnal storage**	**B) with seasonal storage**
<u>Specific</u> cost <u>ready installed</u> [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.54** (+/- 22%) *(0.42 – 0.66)*	**0.64** (+/- 25%) *(0.48 – 0,80)*
<u>Specific</u> cost (<u>material only</u>) [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.47** (+/- 22%) *(0.37 – 0.57)*	**0.54** (+/- 25%) *(0.40 – 0.67)*
<u>Specific</u> cost (<u>labor only</u>) [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.07** *(0.05 – 0.09)*	**0.10** *(0.08 – 0.13)*
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**540** (+/-22%) *(421 – 659)*	**3,200** (+/-24%) *(2,400 – 4,000)*
Fixed O&M per unit [€/m²gross/a]*	3.5	4.0
Variable O&M per unit [€/m²gross/a]**	1.4	1.1

Levelized cost of heat *LCOH* [€-ct/kWh] *- range (from - to)*	**9.2** (+/- 21%) *7.3 – 11.2*	**14.0** (+/- 24%) *10.6 – 17.4*

* 0.75% of net investment cost (excl. labor)

** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh

Table 6: Benchmarks for <u>ground-mounted</u> solar thermal systems connected to (district) heating grids (size of sample: 11)

Solar thermal system category	SDH: Solar district heating Solar assisted district heating (ground mounted collector field)	
All systems of this category are **ground-mounted** and may be equipped with either - short-term (diurnal) storages **(A)** or - long-term (seasonal) storages **(B)**		
Energy/technical data	**A) with diurnal storage**	**B) with seasonal storage**
Kind of solar thermal collector used *optional*	**FPC** -	**FPC** -
Kind of solar energy storage used *optional*	Non-pressurized TTES *pressurized TTES*	PTES *BTES, (ATES)*
Typical size per unit [m²gross] *- range (from - to)*	**10,000** *5,000 – 20,000 (up to 150,000)*	**50,000** *20,000 – 70,000*
Typical thermal peak capacity per unit [kW] *- range (from - to)*	**7,000** *3,500 – 14,000*	**35,000** *14,000 – 140,000*
Typical storage volume per unit [m³.H2Oe]	**1,200**	**125,000**
Typical annual production per unit [MWh/a]	**4,100**	**17,500**
Specific **storage volume per unit** [ltr./m²gross] *- range (from - to)*	**120** *90 – 150*	**2,500** *1,500 – 3,500*
Typical solar energy yield *SE* [kWh/m²gross/a] *- range (from - to)*	**410** *380 – 460*	**365** *340 – 390*
Typical solar fraction sf [-] *- range (from - to)*	**12%** *5 – 20%*	**50%** *40 – 60%*
Technical life time [years]	25	25
Financial data	**A) with diurnal storage**	**B) with seasonal storage**
<u>Specific</u> cost <u>ready installed</u> [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.24** (+/- 12%) *(0.21 – 0.27)*	**0.29** (+/- 15%) *(0.25 – 0,33)*
<u>Specific</u> cost (<u>material only</u>) [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.22** (+/- 12%) *(0.19 – 0.25)*	**0.27** (+/- 15%) *(0.23 – 0.31)*
<u>Specific</u> cost (<u>labor only</u>) [1,000€/m²gross] (excl. VAT, excl. subsidies)	**0.02** *(0.02 – 0.02)*	**0.02** *(0.01 – 0.02)*
Investment per unit ready installed [1,000€/unit] (excl. VAT, excl. subsidies)	**2,400** (+/-12%) *(2,100 – 2,700)*	**14,500** (+/-15%) *(12,325 – 16,675)*
Fixed O&M per unit [€/m²gross/a]*	1.7	2.0
Variable O&M per unit [€/m²gross/a]*	1.5	1.3

Levelized cost of heat *LCOH* [€-ct/kWh] - range *(from - to)*	4.1 (+/- 11%) 3.7 – 4.6	5.5 (+/- 14%) 4.7 – 6.3

* 0.75% of net investment cost (excl. labor)
** Electricity for solar pump and control (around 1.5 kWh electrical / 100 kWh heat produced). Electricity: 24€-ct/MWh

Note: For solar district heating systems with no additional diurnal or seasonal storage attached specific costs have to be reduced by respective costs for thermal energy storages as presented in chapter 4.1.4.

4.1.1 Solar energy yield per system category (Central European climate)

Solar energy yield *SE* is referred to as *specific* annual *useful* thermal energy delivered by the solar thermal system in kWh per m² gross collector area installed. *SE* mainly depends on the kind of solar thermal collector installed (flat plate or evacuated tube collector), yearly sum of global solar irradiation onto the collector surface $G_{0,incl}$, the temperature level solar thermal energy is provided as well as the solar fraction *sf* (cf. chapter 2.1).

In Figure 5 next a typical range of solar energy yields for well-designed and proper working solar thermal systems with flat plate collectors are shown for each solar thermal system category investigated. As all the analyzed systems are located in Northern resp. Central Europe the specific yields are valid for the respective yearly sum of global solar irradiation onto the collector surface in this climatic region [12].
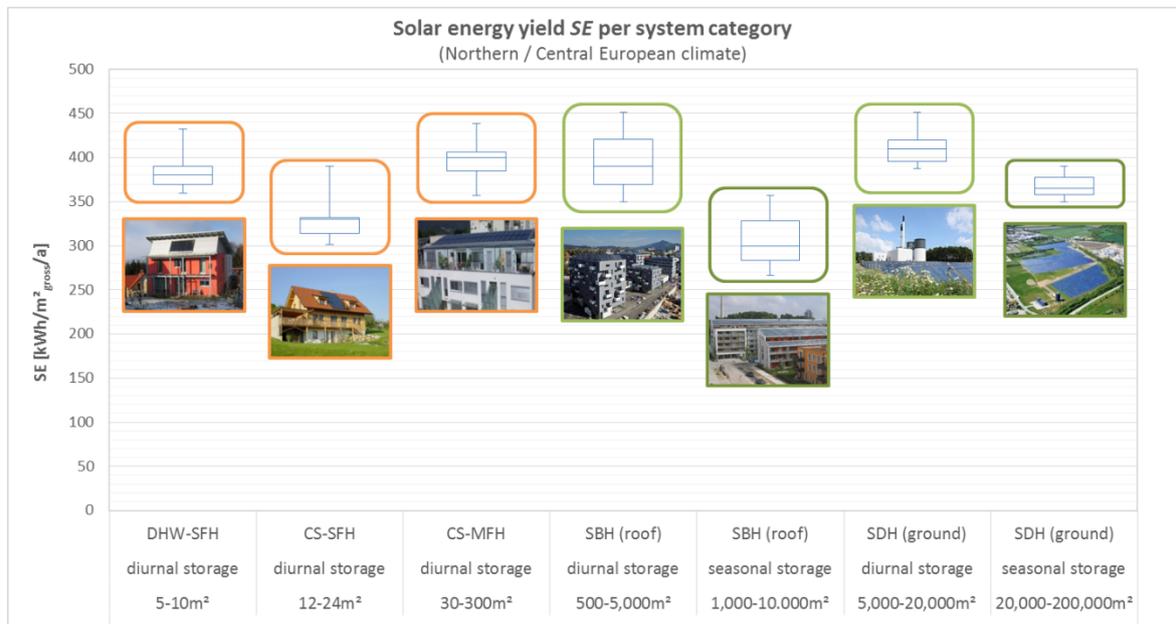
Figure 5: Solar energy yield per system category (valid for Central European climate)

For solar thermal systems in single-family homes typical annual solar energy yields range from 360-430 kWh/m²$_{gross}$ for domestic hot water systems (DHW-SFH) and from 300-390 kWh/m²$_{gross}$ for solar-combi systems (CS-SFH). With larger solar thermal systems especially designed for the supply of multi-family homes (CS-MFH) annual yields of between 360-440 kWh/m²$_{gross}$ are reached.

For solar thermal systems with diurnal storages connected to thermal grids experiences from Austria and Denmark proof that annual solar energy yields of between 380-450 kWh/m²$_{gross}$ can be expected if the thermal grid is operated at low supply (70-80°C) and return (45-55°C) temperatures. Solar energy yields of >500 kWh/m²$_{gross}$ are possible if thermal grid supply and return temperatures are lower (e.g.: 65/40) as monitoring data from various SDH plants in Denmark **/20/** proof.

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[12] Yearly sum of global irradiation on optimally inclined surfaces $G_{0,incl}$ in the investigated Northern/Central Europe countries in this report are 1,280 kWh/(m²·a) @34° in Wurzburg, DE 1,290 kWh/(m²·a) @40° in Copenhagen, DK and 1,460 kWh/(m²·a) @37° in Graz, AT (source: http://re.jrc.ec.europa.eu/pvgis/).

If seasonal storages are used, solar energy yield typically decreases due to higher thermal losses. Basically, thermal losses are lower in larger thermal storages than in smaller ones due to a better surface to volume ratio. Compared to conventional applications with short-term (diurnal) storages it may be assumed that *SE* is reduced by 20-30 % when using seasonal storages of between 2,500-25,000 m³ in block heating grids (E_{Solar} ~250-350 kWh/m²$_{gross}$/a) and by 10-20 % when using seasonal storages of between 50,000-500,000 m³ in district heating grids (E_{Solar} ~350-400 kWh/m²$_{gross}$/a).

4.1.2 Approximation of solar energy yields for other climatic regions

Solar energy yields *SE* presented in chapter 4.1.1 are valid for *average* Northern and Central European annual global solar irradiation values onto optimally inclined collector surface $G_{0,incl}$ of 1,343 kWh/(m²·a). For quick estimations, solar energy yields for any location SE_{var} may be approximated assuming a linear relationship between *SE* in Northern/Central Europe and the ratio between annual global solar irradiation at the new location $G_{0,incl,var}$ and the average annual global solar irradiation $G_{0,incl}$ in Northern/Central Europe (Eq. 4) [13].

$$SE_{var} = SE \cdot \frac{G_{0,incl,var}}{G_{0,incl}} \qquad \text{Eq. 4}$$

In Table 7 solar energy yields (average values as well as typical range) valid for Northern/Central European climates for each solar thermal system category investigated are summarized.

Table 7: Average solar energy yields per system category (valid for Central European climate)

Solar thermal system category	Kind of solar energy storage	Typical size per unit [m²$_{gross}$]	Average solar yields [kWh/(m²·a)]	Typical range of solar yields [kWh/(m²·a)]
DHW-SFH	*diurnal*	*5-10 m²*	$SE_{DHW-SFH}$ = 380	$SE_{DHW-SFH}$ = 360-430
CS-SFH	*diurnal*	*12-24 m²*	SE_{CS-SFH} = 330	SE_{CS-SFH} = 300-390
CS-MFH	*diurnal*	*30-300 m²*	SE_{CS-MFH} = 400	SE_{CS-MFH} = 360-40
SBH	*diurnal*	*500-5,000 m²*	SE_{SBH} = 390	SE_{SBH} = 350-450
SBH	*seasonal*	*1,000-10,000 m²*	$SE_{SBH\_seasonal\ storage}$ = 300	$SE_{SBH\_seasonal\ storage}$ = 270-360
SDH	*diurnal*	*5,000-20,000 m²*	SE_{SDH} = 410	SE_{SDH} = 390-450
SDH	*seasonal*	*20,000-200,000 m²*	$SE_{SDH\_seasonal\ storage}$ = 365	$SE_{SDH\_seasonal\ storage}$ = 350-390

In Table 8 next approximated solar energy yields applying Eq. 4 and considering annual global solar irradiation values onto optimally inclined collector surface $G_{0,incl}$ in Sweden, Switzerland and Portugal are summarized [14].

Table 8: Approximated solar energy yields for different solar thermal system categories considering different yearly sums of global irradiation on optimally inclined surfaces in Sweden, Switzerland and Portugal

Country	Sweden	Switzerland	Portugal
Reference climate	*Gothenburg*	*Zurich*	*Lisbon*
$G_{0,incl}$	*1,330*	*1,420*	*2,020*
Opt. inclination angle I_{opt}	*42°*	*35°*	*34°*
Specific solar energy yield per system category [kWh/m²a]			
$SE_{DHW-SFH}$	*376*	*402*	*571*

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[13] The methodology explained in this chapter may be applied for pre-analysis and quick estimations for both solar energy yields and corresponding levelized costs (cf. chapter 4.1.6). For more accurate solar yield and levelized cost assessments simulations are needed.

[14] Optimally inclined collector surface assuming fixed orientation (=angle relative to the direction due South) and inclination (=angle from the horizontal plane) angles for the entire year. Annual global solar irradiation values onto optimally inclined collector surface $G_{0,incl}$ as well as the optimum inclination angle I_{opt} can be determined for any location here: Photovoltaic Geographical Information System (PVGIS)

$SE_{CS\text{-}SFH}$	327	349	496
$SE_{CS\text{-}MFH}$	396	423	601
SE_{SBH}	386	412	586
$SE_{SBH\_seasonal\ storage}$	297	317	451
SE_{SDH}	406	433	617
$SE_{SDH\_seasonal\ storage}$	361	386	549

4.1.3 Specific thermal energy storage volume per system category

Most solar thermal systems installed today are attached to water-based short-term resp. diurnal storages in order to match intermittent solar irradiation with thermal energy demand for several hours up to a few days. In case solar thermal energy provided in summer should be available in autumn or even in winter energy has to be stored for several weeks and hence so called long-term or seasonal storages are needed.

For short-term (diurnal) storage of solar thermal energy and load balancing specific solar energy storage volume of between 50 and 150 liters per m² of installed collector area is needed. By contrast, long-term (seasonal) storage of solar thermal energy demands specific solar energy storage volume of between 1,500 and 3,500 liters per m² of installed collector area (Figure 6).
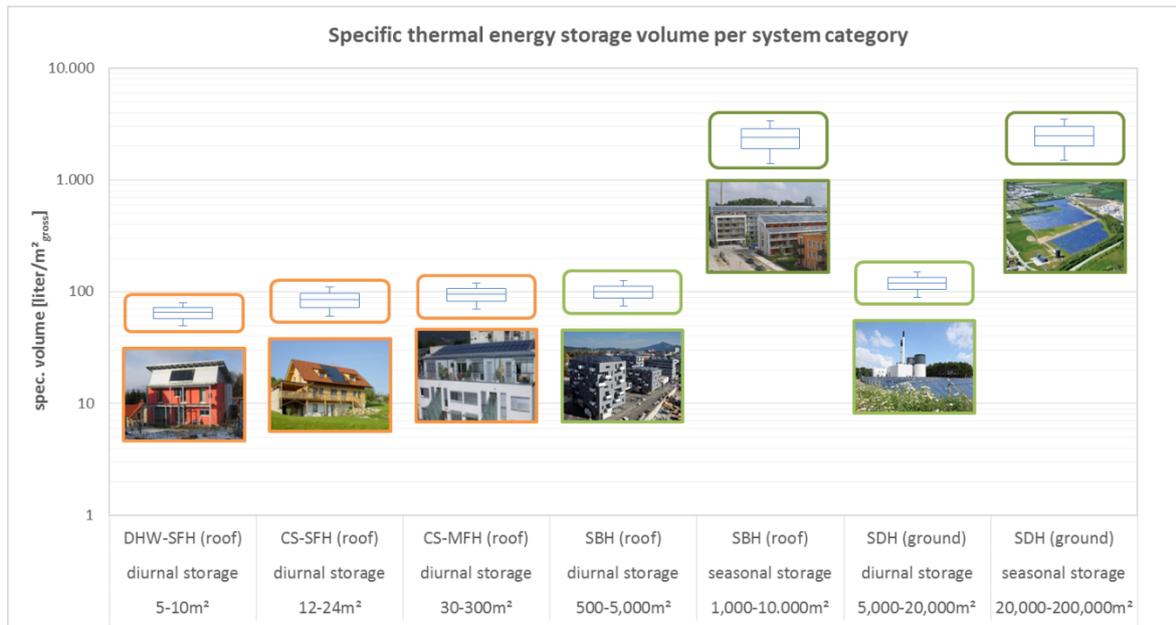
Figure 6: Specific thermal energy storage volume per solar thermal system category

For solar assisted domestic hot water preparation in single family homes (DHW-SFH) average specific storage volume of 65 liter/m²gross is needed (range: 50-80 liter/m²gross) to provide 60–75% of the annual domestic hot water (DHW) demand with solar thermal. Solar combi systems in single and multi-family homes (CS-SFH; CS-MFH) demand a bit larger specific storage volumes of between 60-110 liter/m²gross in order to provide 10–40% of the annual DHW + space heating demand (highly depending on building standard). For large-scale solar thermal systems connected to heating grids (SBH, SDH) the specific solar energy storage volume depends on various parameters but as a rule of thumb 100-150 liters/m²gross for diurnal storages may be used as a design parameter in an early project phase. With diurnal storages solar fractions of between 5-15% can be reached.

Typical specific solar energy storage volumes for seasonal storages range from 1,400-3,600 litre/m²gross and have been realized in Germany, Sweden and most recently in Denmark and Canada

(chapter 4.2). With seasonal thermal storages typically solar fractions of between 40-80% (block heating) and 45-55% (district heating) can be achieved.

4.1.4 Specific thermal energy storage costs

Specific costs for thermal energy storages are highly sensitive to the storage technology applied as well as to the storage volume per unit.

Specific costs for tank thermal energy storages (TTES)

Solar thermal systems for hot water preparation only are usually attached to domestic hot water tanks made of carbon steel with enamel coating on the inside and with one or two internal spiral-shaped heat exchangers. Typical domestic hot water tank sizes range between 200 and 800 liters and average specific costs lie between 2,400 €/m³ and 1,250 €/m³ respectively. Solar combi-systems for DHW and space heating are usually attached to pressurized carbon steel tanks with either internal or external heat exchangers. Typical storage sizes in single family homes are 800 to 2,000 liters with average specific costs of 1,350 €/m³ and 950 €/m³ respectively. In multi-family homes respective larger units of between 5,000 and 30,000 liters are used with specific costs down to below 850 €/m³.

For large scale solar thermal systems connected to heating grids either pressurized carbon steel tanks or non-pressurized tanks are used. The latter are either made of stainless steel or other technical measures are needed in order to avoid corrosion in the tank. Pressurized carbon steel tanks are applied up to storage volumes of around 500 m³ (with costs down to below 750 €/m³). For larger storage volumes of >500 m³ up to 50,000 m³ usually non-pressurized tanks are getting increasingly cheaper (lowest costs down to below 130 €/m³). In Figure 7 next, specific cost curves (specific costs c in €/m³ as function of storage volume $V_{Storage}$ in m³) for domestic hot water tanks as well as for pressurized and non-pressurized TTES are plotted (dotted lines represent upper and lower limits). Below, the fitted cost curve functions for the average spec. costs (solid lines in Figure 7) are given.
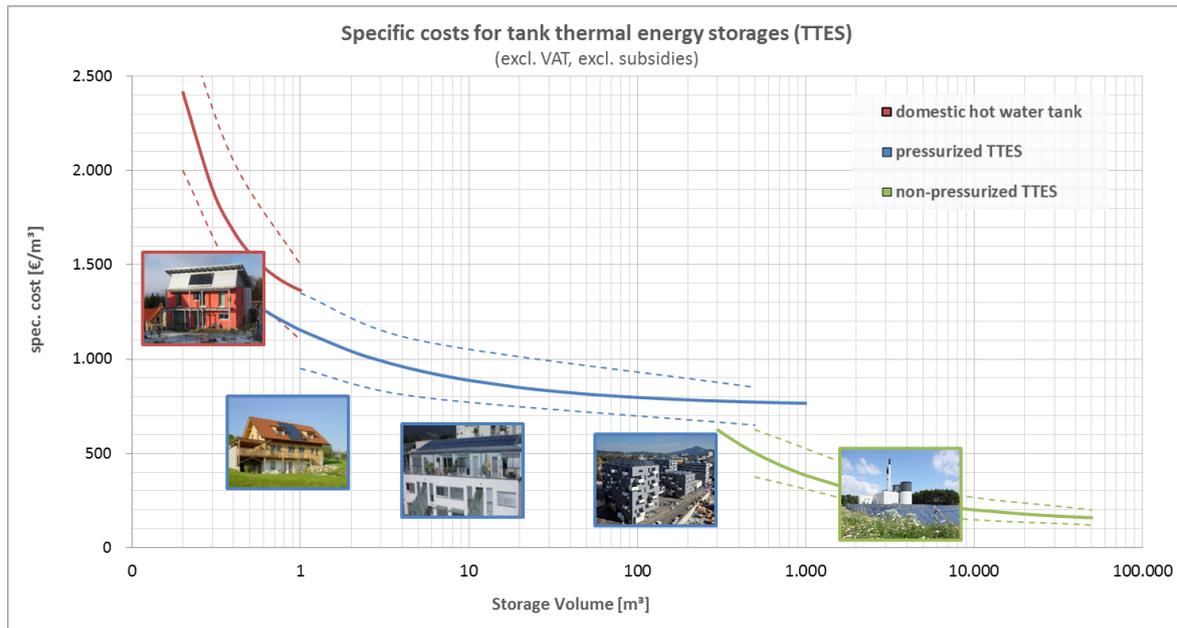
Figure 7: Cost curves for different tank thermal energy storage technologies (incl. insulation; excl. VAT, excl. subsidies)

Cost function for domestic hot water tanks (0.2 m³ – 1.0 m³):

$$c_{DHW-tank}(V_{storage}) = 114.5 \cdot V_{storage}^{-1.441} + 1{,}250 \qquad\qquad \text{Eq. 5}$$

Cost function for pressurized carbon steel tanks (0.5 m³ – 500 m³):

$$c_{TTES_{pressurized}}(V_{storage}) = 403.5 \cdot V_{storage}^{-0.4676} + 750 \qquad\qquad \text{Eq. 6}$$

Cost function for non-pressurized (stainless) steel tanks (500 m³ – 50,000 m³):

$$c_{TTES_{non-pressurized}}(V_{storage}) = 11{,}680 \cdot V_{storage}^{-0.5545} + 130 \qquad\qquad \text{Eq. 7}$$

Specific costs for long-term (seasonal) storages

For long-term (seasonal) storage of solar thermal generated heat four different seasonal storage technologies are available on the market today: aquifer thermal energy storages (ATES), borehole thermal energy storages (BTES), pit thermal energy storages (PTES) and non-pressurized tank thermal energy storages (TTES). Storage media is water (ATES, PTES and TTES), water/gravel (PTES) or ground/soil (BTES) [15].

Costs for non-pressurized TTES go down to below 150 €/m³ (for very large applications up to 50,000 m³ costs of 130 €/m³ are possible). Non-pressurized TTES may be installed close to the boiler house of a district heating plant or may be buried underground in dense urban areas. For even larger applications BTES and PTES might be installed. BTES with water equivalent storage volumes of up to 20,000 m³ have been demonstrated in Denmark, Germany and Canada with specific costs down to 65€/m³. In conceptual studies costs below 30 €/m³ for larger BTES up to 100,000 m³ water equivalent are published /22/. Largest thermal energy storages were built in Denmark applying PTES technology with specific costs ranging from 80€/m³ for a 10,000 m³ installations to 28€/m³ for a 200,000 m³ installation /23/.

In Figure 8 next, specific cost curves for very large (>1,000 m³) non-pressurized TTES, BTES and PTES are plotted (dotted lines represent upper and lower limits). Below, the fitted cost curve functions for the average spec. costs are given for BTES (Eq. 8) and PTES (Eq. 9) (non-pressurized TTES = Eq. 7).
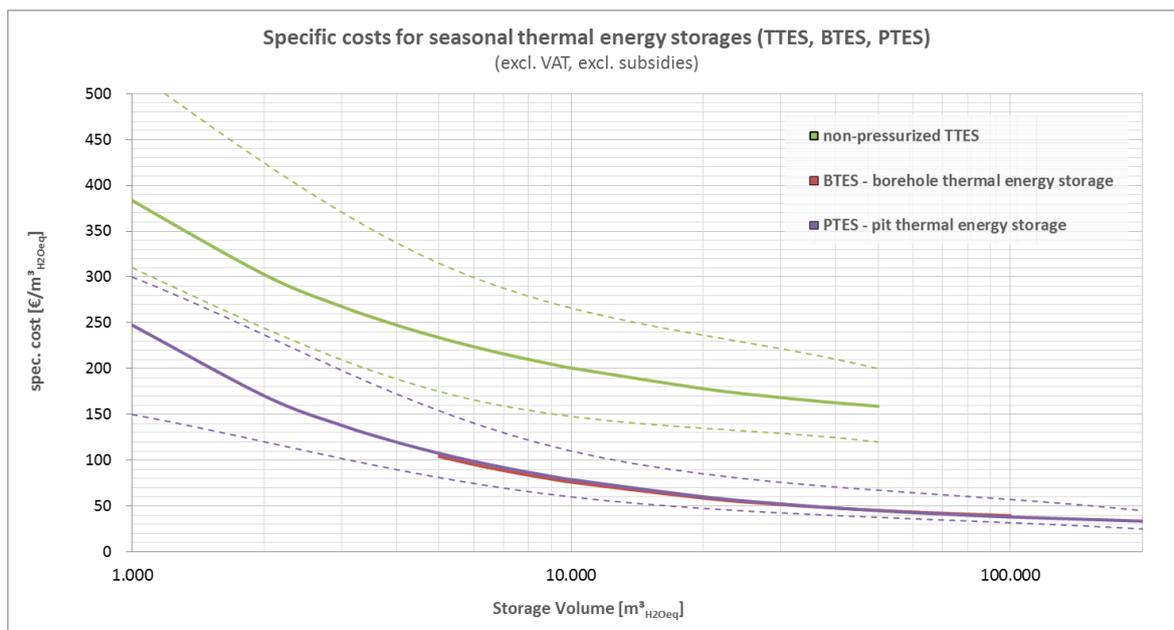
Figure 8: Cost curves for different long-term (seasonal) storage technologies (excl. VAT, excl. subsidies)

Cost function for BTES - borehole thermal energy storages (5,000 m³ – 100,000 m³):

$$c_{BTES}(V_{storage}) = 25{,}330 \cdot V_{storage}^{-0.685} + 30 \qquad \text{Eq. 8}$$

Cost function for PTES - pit thermal energy storages (1,000 m³ – 200,000 m³):

$$c_{PTES}(V_{storage}) = 15{,}630 \cdot V_{storage}^{-0.6156} + 25 \qquad \text{Eq. 9}$$

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[15] More information about seasonal heat storages can be found here (in German language): http://www.saisonalspeicher.de/ or here **/21/**

4.1.5 Specific solar thermal system costs

Cost data presented in this chapter refer to end-user (customer) prices of ready-installed (turnkey) systems excluding value added taxes (VAT) or subsidies. Specific costs are referred to gross collector area installed ($€/m^2_{gross}$). Main differences in solar thermal system costs refer to A) the size per unit (m² collector area), B) mounting option (ground/roof) and C) kind of storage used (diurnal/seasonal). In general, scaling effects regarding both the size of the solar thermal collector field as well as the size of the thermal energy storage unit have significant impact on the overall specific costs.

In Figure 9 next, typical range of specific costs for ready installed solar thermal systems (turn-key costs) are shown for each system category investigated.
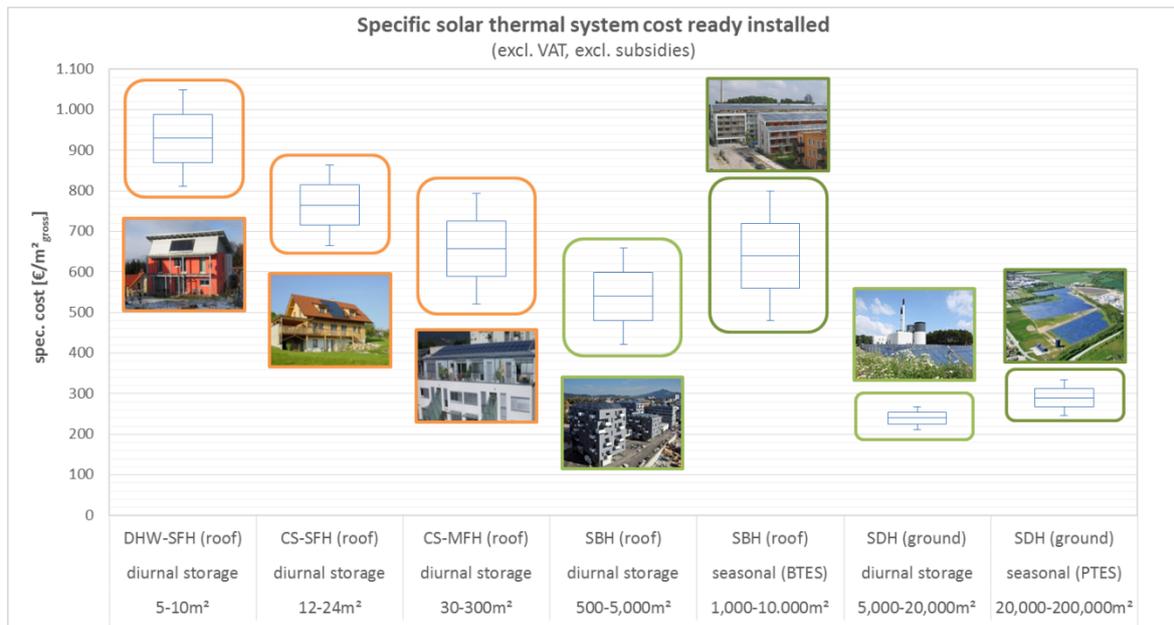
Figure 9: Typical range of specific costs per solar thermal system category ready installed (excl. VAT, excl. subsidies); <u>orange</u>: ST systems in single and multi-family homes with diurnal storage; <u>light green</u>: ST systems connected to thermal grids with diurnal storage; <u>dark green</u>: ST systems connected to thermal grids with seasonal storage

Average specific costs for roof mounted systems <u>with diurnal storage</u> range from 930 $€/m^2_{gross}$ (+/- 13%) for small scale domestic hot water systems in single family homes (DHW-SFH) to 770 $€/m^2_{gross}$ (+/- 13%) for combi-systems in single-family homes (CS-SFH) and down to 660 $€/m^2_{gross}$ (+/- 21%) for combi-systems in multi-family homes (CS-MFH).

With larger roof-mounted solar thermal systems (>500 m^2_{gross}) connected to block heating grids (SBH) specific average costs down to 540 $€/m^2_{gross}$ (+/- 12%) are realistic (<u>incl. diurnal storage</u>). Significantly lower average costs of 240 $€/m^2_{gross}$ (+/- 12%, <u>incl. diurnal storage</u>) may be achieved with large-scale ground mounted collector fields (5,000-20,000 m^2_{gross}) hydraulically connected to district heating networks (SDH) [16].

Specific costs for ready installed solar thermal systems <u>with seasonal storage</u> are lowest for very large ground-mounted installations (50,000-200,000 m^2_{gross}) hydraulically connected to district heating networks. Large scale installations with pit thermal energy storages (PTES) attached have been realized in Denmark with specific turnkey-costs of 290 $€/m^2_{gross}$ (+/- 15%). Costs for smaller (e.g. 5,000 m^2_{gross}), roof mounted installations with seasonal storages connected to block heating grids lie between 750 $€/m^2_{gross}$ (+/- 22%) for systems with non-pressurized tank thermal energy storages (TTES) and 640 $€/m^2_{gross}$ (+/- 25%) for systems with borehole thermal energy storages (BTES).

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[16] In many Danish large-scale SDH installations existing CHP load balancing storages are used to balance peak solar thermal heat generation as well. In these cases no additional thermal storage is needed and specific solar thermal system costs go down to 190 $€/m^2_{gross}$.

Cost curves for solar thermal systems with short-term (diurnal) storages attached

In Figure 7 next, specific cost curves (specific costs c in €/m²$_{gross}$ as function of collector field size A_{coll} in m²$_{gross}$) for *ready-installed* roof-mounted as well as large ground mounted solar thermal systems *with diurnal storage* are plotted (dotted lines represent upper and lower limits).

Below, the fitted cost curve functions for roof mounted (Eq. 10) and ground mounted (Eq. 11) solar thermal systems within a typical range of applicable solar thermal system sizes are given.

It can be seen that A) with larger units significantly lower costs can be achieved and B) that today large roof-mounted systems approach an average lower cost limit of 500 €/m²$_{gross}$ whereas with large ground-mounted installation specific costs down to below 200 €/m²$_{gross}$ are possible.

Moreover, from Figure 10 it is obvious that the confident bounds for small and large roof-mounted systems are much more uncertain than for large-scale ground mounted solar thermal systems. For the latter this is especially due to scaling effects (material costs are highly dominant compared to labor costs) and a high level of standardization whereas especially for large roof-mounted systems customer-designed solutions and usually more complex hydraulic integration of the solar thermal systems in general result in higher and more inhomogeneous costs.
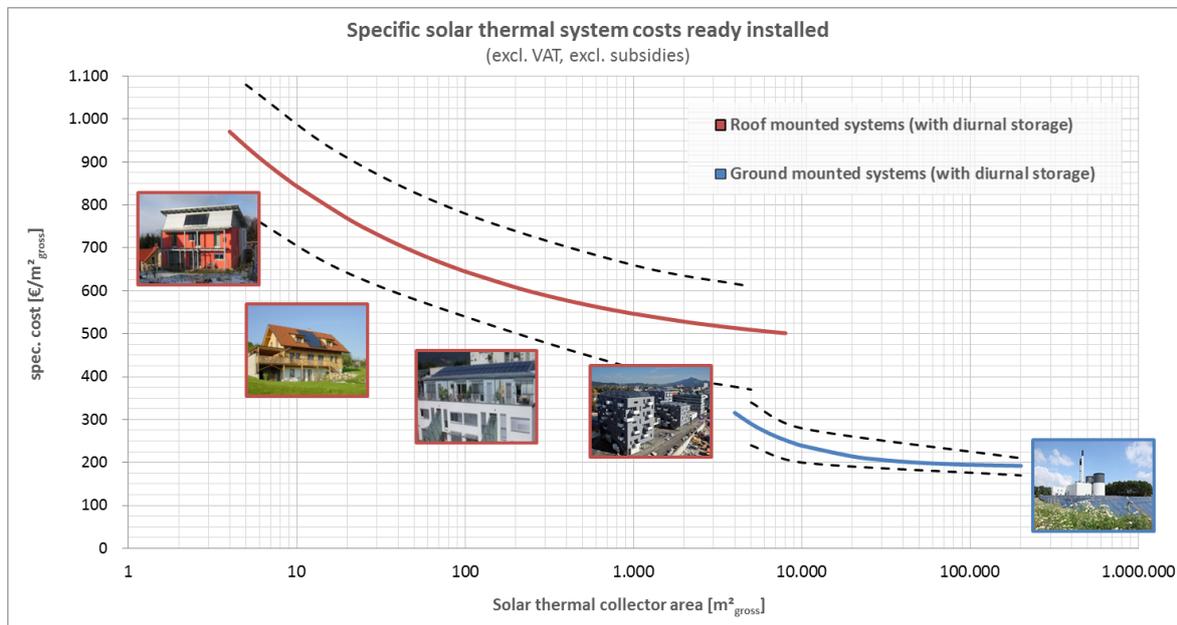
Figure 10: Cost curves for (ready installed) roof mounted and ground mounted solar thermal systems with diurnal storage (excl. VAT, excl. subsidies); red: **roof**-mounted ST systems with diurnal storage; blue: **ground**-mounted ST systems with diurnal storage

Cost function for roof-mounted solar thermal systems (5 – 5,000 m²):

$$c_{roof\ mounted\ systems}(A_{coll}) = \ 794.6 \cdot A_{coll}^{-0.305} + 450 \qquad \text{Eq. 10}$$

Cost function for ground-mounted solar thermal systems (5,000 – 500,000 m²):

$$c_{ground\ mounted\ systems}(A_{coll}) = \ 598,700 \cdot A_{coll}^{-1.021} + 190 \qquad \text{Eq. 11}$$

4.1.6 Levelized cost of solar thermal generated heat (Central European climate)

Levelized cost of solar thermal generated heat $LCOE_{ST}$ is calculated according to Eq. 3 for each solar thermal system category investigated. All calculation parameters and results of the calculation are summarized in Table 9 next. Basis for the calculation are representative costs for ready installed solar thermal systems for each solar thermal system category (cf. chapter 4.1.5) as well as solar energy yields SE typically for Central European climates (cf. chapter 4.1.1).

Table 9: Parameters for $LCOE_{ST}$ calculation and calculated $LCOE_{ST}$ for each system category (Central European climate)

ST system category	DHW-SFH	CS-SFH	CS-MFH	SBH	SBH	SDH	SDH
Installation	roof	roof	roof	roof	roof	ground	ground
Typical size [m²]	5-10m²	12-24m²	30-300m²	500-5,000m²	1,000-10,000m²	5,000-20,000m²	20,000-200,000m²
Typical storage	Day DHW tank	Day TTES pressurized	Day TTES pressurized	Day TTES pressurized	Seasonal BTES	Day TTES-non pressurized	Seasonal PTES
I_0 [1,000 €/m²$_{gross}$]	0.81 - 1.05	0.67 - 0.86	0.52 - 0.79	0.42 - 0.66	0.48 - 0.80	0.21 - 0.27	0.25 - 0.33
SE [kWh/m²$_{gross}$]	380	330	400	390	300	410	365
A_t [€/m²$_{gross}$]	0.008	0.007	0.007	0.005	0.005	0.003	0.003
r [-]	3.0	3.0	3.0	3.0	3.0	3.0	3.0
t_{ges} [a]	25	25	25	25	25	25	25
$LCOE_{ST}$ [€-ct/kWh]	14.3-18.1	13.7-17.4	8.9-13.4	7.3-11.2	10.6-17.4	3.7-4.6	4.7-6.3

$LCOE_{ST}$ range from 13.7-18.1 €-ct/kWh for solar thermal systems in single family homes down to 8.9-13.4 €-ct/kWh for solar thermal systems in multi-family homes. With roof-mounted systems connected to block heating networks and diurnal storages $LCOE_{ST}$ of down to 7.3-11.2 €-ct/kWh are realistic. With large-scale solar district heating plants with diurnal storage lowest $LCOE_{ST}$ of 3.7-4.6 €-ct/kWh are achieved in Denmark. Due to scaling effects, using seasonal storages is most cost effective in connection with very large solar thermal installations - e.g.: $LCOE_{ST}$ for a 5,000 m² roof-mounted solar block heating installation with 12,500 m³ BTES is between 10.6-17.4 €-ct/kWh whereas $LCOE_{ST}$ for a 50,000 m² ground-mounted solar district heating installation with 125,000 m³ PTES is between 4.7-6.3 €-ct/kWh (Figure 11).
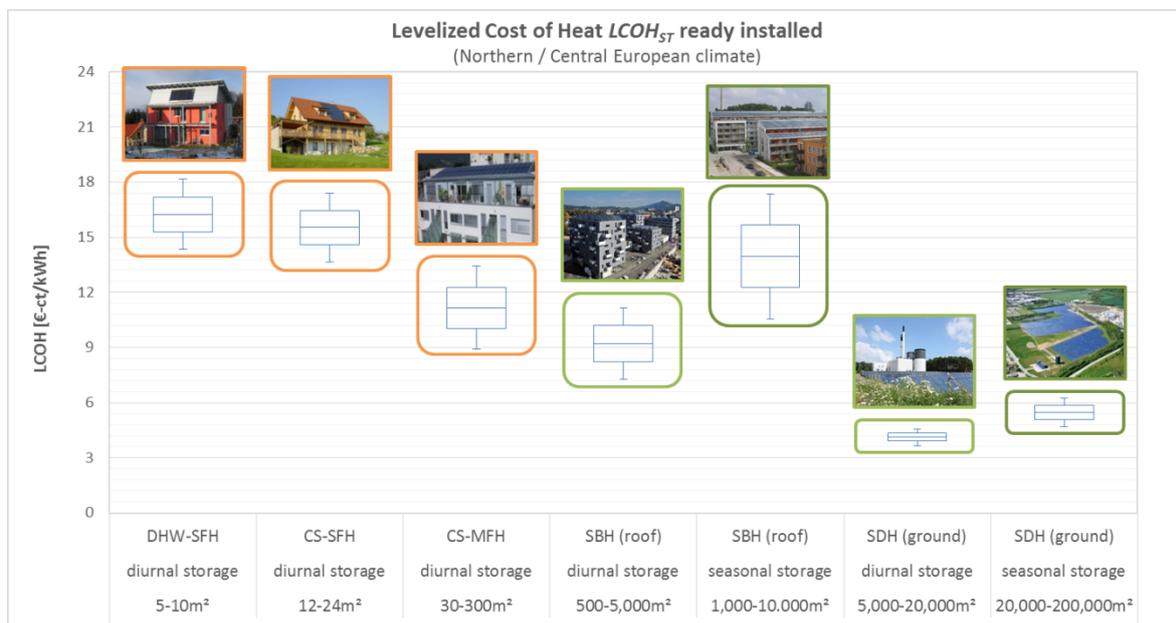
Figure 11: Typical range of $LCOE_{ST}$ for ST generated heat per system category (reference: Central European climate)

4.1.7 Levelized cost of solar thermal generated heat (Southern Europe climate)

For the calculation of levelized cost of solar thermal generated heat $LCOE_{ST}$ in other climatic regions than North and Central Europe solar energy yield SE may be approximated according to Eq. 4 (cf. chapter 4.1.2). In Table 10 next, all calculation parameters as well as the results of the $LCOE_{ST}$ calculation assuming Southern European climate (reference: Lisbon [17]) are summarized.

Table 10: Parameters for LCOE calculation and calculated LCOH for each system category (Southern European climate)

ST system category	DHW-SFH	CS-SFH	CS-MFH	SBH	SBH	SDH	SDH
Installation	roof	roof	roof	roof	roof	ground	ground
Typical size $[m^2]$	5-10m²	12-24m²	30-300m²	500-5,000m²	1,000-10,000m²	5,000-20,000m²	20,000-200,000m²
Typical storage	Day DHW tank	Day TTES pressurized	Day TTES pressurized	Day TTES pressurized	Seasonal BTES	Day TTES-non pressurized	Seasonal PTES
I_0 $[1,000\ €/m^2_{gross}]$	0.81 - 1.05	0.67 - 0.86	0.52 - 0.79	0.42 - 0.66	0.48 - 0.80	0.21 - 0.27	0.25 - 0.33
SE $[kWh/m^2_{gross}]$	571	496	601	586	451	617	549
A_t $[€/m^2_{gross}]$	0.008	0.007	0.007	0.005	0.005	0.003	0.003
$r\ [-]$	3.0	3.0	3.0	3.0	3.0	3.0	3.0
$t_{ges}\ [a]$	25	25	25	25	25	25	25
$LCOE_{ST}$ $[€\text{-}ct/kWh]$	9.7-12.2	9.2-11.7	6.1-9.0	5.0-7.5	7.1-11.7	2.6-3.2	3.3-4.3

Due to the higher yearly sum of global irradiation $G_{0,incl}$ in Southern Europe (e.g. Lisbon with 2,020 kWh/m²/a) compared to Northern Europe (e.g. Wurzburg with 1,390 kWh/m²/a) and the correspondingly higher solar energy yields SE (cf. chapter 4.1.2) levelized cost of solar thermal generated heat $LCOE_{ST}$ may be reduced by around 30 % (assuming same techno-economic boundary conditions).
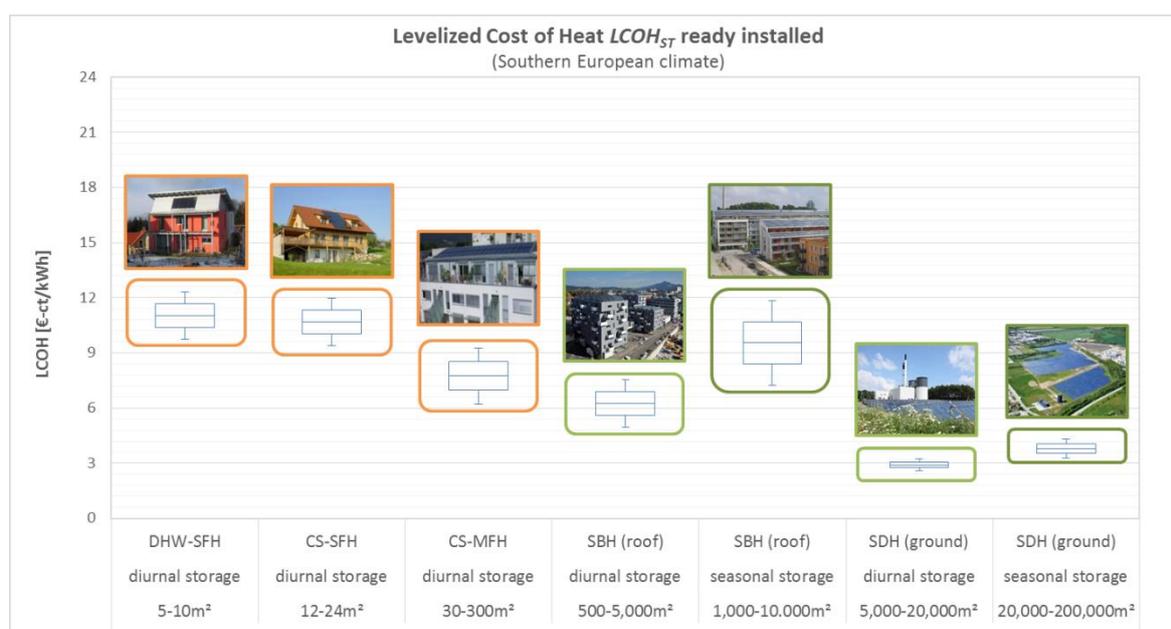
Figure 12: Typical range of $LCOE_{ST}$ for ST generated heat per system category (reference: Southern European climate)

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[17] Yearly sum of global irradiation on optimally inclined surfaces in Lisbon, PT: 2,020 kWh/(m²·a) (source: http://re.jrc.ec.europa.eu/pvgis/)

5   Summary

In the present report solar thermal system configurations suitable for applications in urban environments are identified and characterized by representative techno-economic benchmark figures from a set of best practice examples. Objective of this report is to provide a comprehensive data base for techno-economic (pre-) evaluations regarding the role of solar thermal in urban energy systems, especially applicable for urban planners / energy system planners without deeper theoretical solar thermal expertise.

Classification and benchmarking of solar thermal systems in urban environments

Urban environments provide a wide range of possibilities for the (hydraulic) integration of solar thermal systems. Basically, one may distinguish between solar thermal systems which are directly attached to individual buildings (residential or non-residential buildings) and solar thermal systems which are hydraulically connected to a thermal grid (block heating or district heating grid) for the supply of multiple buildings (Figure 13).

— district heating
— block heating
● Boiler
■ Solar thermal
■ buildings

Figure 13: Overview over solar thermal system concepts in urban environments by means of a virtual study area

Solar assisted heating of individual buildings

Solar assisted heating of individual buildings is commonly applied in countries all over the world and may be applied for various kinds of buildings covered by a city or town (e.g. single and multi-family homes, terraced houses, apartment blocks, hotels, schools, hospitals, production halls, etc.). Especially in Central and North Europe, North America and Australia the majority of solar thermal systems attached to individual buildings are pumped systems (closed loops with forced circulation) equipped with flat plate collectors. Characteristic state of the art applications are building integrated (on-roof, in-roof) and supply thermal energy directly to the building's heating network for either domestic hot water (DHW) or both DHW and space heating (the latter are referred to as "*solar combi-systems*"). Usually, this kind of solar thermal applications are part of bivalent or multivalent building heating and cooling systems including diurnal thermal energy storages for the efficient utilization of the energy gains from the solar thermal system.

Typical solar thermal system sizes for DHW-systems in single-family homes are between 5-10 m² (1.5-2.5 m² per person). Mostly, DHW tanks with specific storage volumes of between 50-80 liter/m²$_{gross}$ are attached to provide 65–75% of the annual DHW demand with solar thermal. Solar-combi systems in single-family homes are typically larger with system sizes of between 12-24 m² (3-5 m² per person). Typical solar fractions of the annual DHW + space heating demand range between 15–35% (highly depending on the building standard!) and specific storage volumes range from 60-

110 liter/m²$_{gross}$. Depending on the number of dwellings, solar thermal systems for multi-family homes are correspondingly larger (30-300 m²). Typically, 0.8-1.5 m² collector area per person are necessary to provide 60–70% of the annual DHW demand resp. 10-15 % of the annual DHW + space heating demand with solar thermal. Average specific solar energy storage volumes of between 70-120 liter/m²$_{gross}$ are commonly attached.

Average specific costs range from 930 €/m²$_{gross}$ (+/- 13%) for domestic hot water systems in single family homes (5-10 m² collector area) to 770 €/m²$_{gross}$ (+/- 13%) for combi-systems in single-family homes (12-24 m² collector area) and down to 660 €/m²$_{gross}$ (+/- 21%) for combi-systems in multi-family homes (30-300 m² collector area). Corresponding levelized costs for solar thermal generated heat considering Central European climates amount to 13.7-18.1 €-ct/kWh for solar thermal systems in single family homes down to 8.9-13.4 €-ct/kWh for solar thermal systems in multi-family homes [18]. Assuming same techno-economic boundary conditions but Southern European climate levelized costs go down to 9.4-12.3 €-ct/kWh for solar thermal systems in single family homes and to 6.2-9.3 €-ct/kWh for solar thermal systems in multi-family homes [19].

Solar assisted heating of multiple buildings via thermal grid

In dense urban areas multiple buildings up to whole cities may be attached to block or district heating grids. With block heating multiple buildings in a neighborhood are jointly connected whereas with district heating communities up to whole cities are supplied with thermal energy via a common heating network. Solar thermal systems connected to block or district heating grids have been applied in Europe since the early 1980's. In sum, around 250 large-scale applications >350 kW$_{th}$ (500 m²) exist with Denmark by far being the leader in this market segment and with smaller niche markets in Austria, Germany, Spain and Greece.

In case of **solar assisted district heating (SDH)**, solar thermal systems are part of larger district heating systems consisting of widespread pipe networks and various (distributed) energy conversion technologies and storages. Best practice examples show that solar-thermal feed-in may be centralized (close to the boiler house/ heating plant) or distributed (at any point of the thermal grid). Depending on space availability installation of the collectors may be possible on ground or on roofs. Most of the realized SDH plants do have short-term (diurnal) storages attached in order to utilize the energy gains from the sun most efficiently. With specific storage volumes of between 80-160 liters per m² of installed collector area solar fractions of between 5-15% of the annual district heating demand may be reached. SDH plants with seasonal pit thermal energy storages PTES) realized in Denmark enable solar fractions of 45-55%. Here, significantly larger specific storage volumes of between 1,500-3,500 liters per m² of installed collector area are necessary. Also no storage concepts have been realized in connection with large district heating grids with constant base load heat demand (e.g. Graz, AT). No storage concepts limit solar fractions to around 1-2% of DH demand.

In case of **solar assisted block heating (SBH)**, solar thermal systems are part of a block heating system where multiple buildings of a neighbourhood are connected via a local heating grid. Especially new and renovated building blocks and urban quarters with low heating demand show high potential for the efficient utilization of solar energy. Solar thermal systems attached to block heating networks are typically building integrated and may supply thermal energy either directly to the building attached and/or to the thermal grid connected. Solar energy storages may be attached to the buildings (mostly diurnal storages) and/or to the heating network (can be diurnal, weekly or seasonal storages) connected. Typical solar fractions of solar assisted block heating systems range from 15-25% for installations with diurnal storages and from 45-75% for installations with seasonal storages. Solar fractions of > 90% have been successfully demonstrated.

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[18] Assuming avg. yearly sum of global irradiation on optimally inclined surfaces in **Central Europe** (e.g.: AT, DE, CH) of **1,350 kWh/ (m²a)**

[19] Assuming avg. yearly sum of global irradiation on optimally inclined surfaces in **Southern Europe** (e.g.: PT, ES) of **2,000 kWh/ (m²a)**

Costs for solar thermal systems connected to thermal grids (block heating or district heating grids) are very inhomogeneous. Factors influencing the costs most are economies of scale (for both collector field size and storage volume), kind of solar thermal collector field installation (ground or roof-mounted systems) as well as storage technology attached:

E.g.: with larger (500-5,000 m²$_{gross}$) **roof-mounted** solar thermal systems with diurnal storages connected to block or district heating grids as realized in Austria or Germany specific average costs down to **540 €/m²$_{gross}$** ($^+/_-$ 12%) are realistic. Significantly lower average costs of **240 €/m²$_{gross}$** ($^+/_-$ 12%) may be achieved with large-scale **ground mounted** collector fields (5,000-20,000 m²$_{gross}$) hydraulically connected to DH networks as realized more than 70-fold in Denmark.

Corresponding levelized cost of solar thermal generated heat calculate to 7.3-11.2 €-ct/kWh for larger roof-mounted systems (500-5,000 m²) connected to thermal grids and diurnal storages (e.g. Austria). With large-scale (5,000-20,000 m²$_{gross}$) SDH plants with diurnal storage lowest levelized cost of 3.7-4.6 €-ct/kWh are achieved in Denmark. Assuming same techno-economic boundary conditions but Southern European climate levelized costs go down to 5.0-7.5 €-ct/kWh for larger roof-mounted systems and down to 2.6-3.2 €-ct/kWh for large ground-mounted SDH plants.

Using seasonal storages together with solar thermal systems connected to thermal grids is most cost effective and energy efficient in connection with very large solar thermal installations. Reasons are scaling effects as well as reduced thermal losses with larger thermal energy storage volumes (resp. surface to volume ratios).

E.g.: levelized cost for a 5,000 m² roof-mounted solar block heating installation with 12,500 m³ borehole thermal energy storage is between 10.6-17.4 €-ct/kWh whereas levelized cost for a 50,000 m² ground-mounted solar district heating installation with 125,000 m³ pit thermal energy storage is between 4.7-6.3 €-ct/kWh.

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