Task 55 Towards the Integration of Large

SHC Systems into DHC Networks

C-D4. Modular conception and construction

IEA SHC FACT SHEET 55.C-D4

Subject:	Modular conception
Description:	The factsheet gives a high-level definition of designing solar thermal systems for district heating. In addition, *modules* are introduced which can be used for modelling systems and finally, methods for estimating energy yield and costs of systems are described.
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Introduction

The main goal of solar thermal feasibility studies is to propose a scenario for a solar heating system which best fits the customer's needs. However, the optimal system layout is dependent on the consumer demand and other boundary conditions like climate, working temperatures and available space. As a result, the choice for the best scenario is non-trivial. Thus, one of the tasks of a system designer is to decide which technologies need to be used and how to dimension them. While the detailed engineering is typically studied at later steps in feasibility projects, it is important to get rough estimations about the size of the system also in early stages of the project. Ideally, these estimations could be done fast – for example directly at the customer site during the first visit - such that customers get a good idea about the possibilities and feasibility of solar heating systems.

Thus, the aim of this fact sheet is to give an overview of available methods for estimating the dimensions of solar thermal systems. It first describes the process on a high level of abstraction, then gives a rough idea which *modules* are typically used at solar district heating systems and finally describes methods used for dimensioning them (see Figure 1). The fact sheet is intended for readers who want to develop new methods for designing solar heating systems or want to get a better insight about which techniques exist for modelling solar thermal systems.

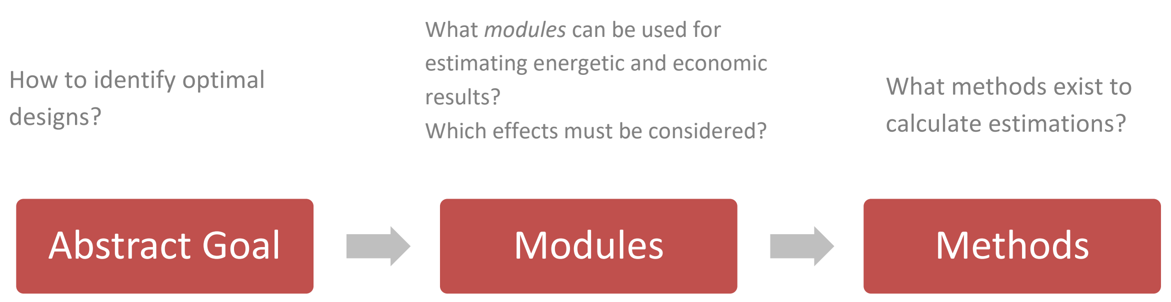

Figure 1: Outline of content of this factsheet.

Contents

Design-Space

To determine a set of system-layouts with high potentials for the customer, the system can be separated into *modules*. Each *module* denotes a part of the system that serves a specific purpose, and which can be scaled (dimensioned) based on that purpose. For example, the solar collector circuit could be regarded as a *module* which purpose is generating heat and which can be dimensioned by the number of collectors used. Hence, the larger the collector area the more heat can be generated, as heat generation scales roughly linearly with the number of collectors. As another example, the heat storage is supposed to store heat and can be scaled by the volume.

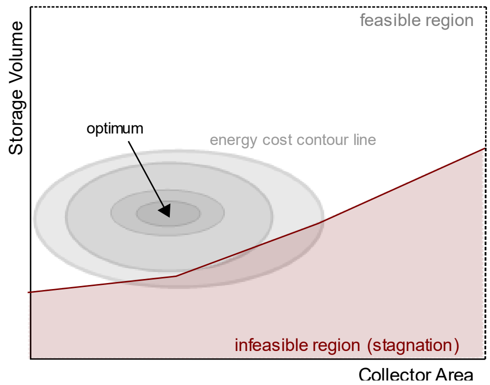

Figure 2: Sketch for 2D design space for heat storage and collector circuit (drawn with Inkscape).

These different modules can be added together to form system layouts. For example, the *solar collector circuit module* could be combined with the *heat storage module* to generate heat and be able to store it when there is no demand at some time. The collector area and the heat store must thus be dimensioned accordingly, to generate enough heat while ensuring that no overheating of the collectors occurs. Naturally, this is dependent on the consumer demand and the weather conditions and appropriate sizes for the *modules* must be found by the system designer.

While this is a two-dimensional example, for more complex systems even more *modules* might be considered, increasing this problem to more dimensions. As an example, a cooler might be added to the system to prevent overheating, which needs to be sized accordingly as well – increasing the dimension to three dimensions.

Put in a more abstract way, the *modules* and their parameters define a multi-dimensional *design space* (Bandyopadhyay, 2012) for solar thermal systems. The task of the designer is thus to extract the most beneficial design based on the boundary conditions of the system, costs and generated energy. It is his/her task to find out where limits of the *modules* apply and determine the economically and energetically best solution. An example sketch of the two-dimensional example *design space* is drawn in Figure 2 for better illustration. Infeasible designs due to stagnation are marked in red and should not be considered by the designer. All designs above the curve are possible, but not necessarily optimal designs. Additionally, the heat price of each configuration in the design space can be calculated and is displayed by the gray contour curves – marking that all designs on this curve correspond to the same heat price. With this information, the designer can easily identify the optimum solution in the feasible region, where the heat price is at its minimum.

To draw this graph, the limits of the design space need to be known and energetic and economic feasibility must be considered. When this knowledge is acquired, however, the task of identifying the best design for the consumer can be done easily.

Modules

Thus, as a first step, *modules* which are used in designing systems are described. The focus is threefold: First, it is essential to know the main purpose of the modules in order to identify the property which needs to be scaled. Second, the parameter essential to dimensioning is justified and described. And third, the limits, external dependencies and other optimization parameters are discussed in order to understand which parameters are typically excluded in the design space and where some dimensioning methods might make assumptions that neglect them.

The discussed *modules* are the solar collector circuit, the heat storage, external heating and heat pumps, as they are often used for designing solar thermal systems for district heating. However, the list makes no claim

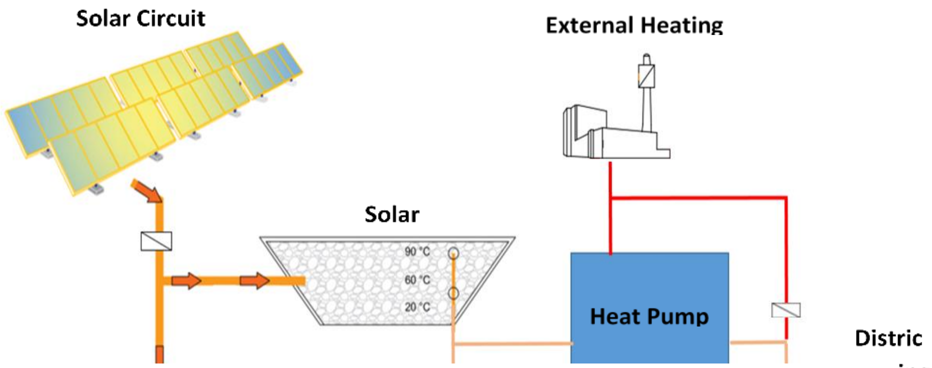

Figure 3: Example layout for solar thermal system for district heating application.

to be complete, but only covers some of the most used modules for district heating. Note that components like pumps, pipes, valves, etc. are included in the *modules* but are not *modules* itself.

Solar Circuit

The solar collector circuit *module* denotes all parts in the primary and secondary solar collector circuit. Naturally, its main purpose is to generate heat, using the solar irradiation as source. Collectors, pipes and valves are incorporated into the same *module* as all these parts need to be installed together to fulfil this purpose. In addition, the heat exchanger – if used – is added to the same *module* as the effect is not large enough to define a new dimension for the solar collector circuit. Moreover, the optimal size for the heat exchanger follows the size of the collector area closely.[1]

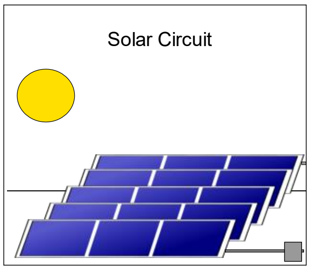

Figure 4: Sketch of solar circuit module.

Scaling:
As the purpose of the module is generating heat, the parameter used in the design space for dimensioning should be able to arbitrarily scale the produced solar yield. While there are a lot of options to optimize the solar collector circuit, the parameter used in the design space for dimensioning is typically the **collector area**. This is the natural choice as the number of collectors can easily be scaled up according to the consumer demand. Based on the solar keymark equations the scaling is approximately linear in the collector aperture area[2]. In contrast, varying the collector orientation, collector type, or amount of pipe-insolation has less effects when compared to standard setups.

Optimization:
To get the most heat from the solar collector circuit there are a lot of options to optimize, apart from the number of collectors used. For example, the orientation and tilt of the collectors can be adjusted to align consumer demand and available radiation. In addition, different collector types can be used based on their efficiency and performance in the relevant climate condition. And finally, the type of insulation or the pipe dimensions can be varied to reduce heat losses and hydraulic issues and the control strategy can be adapted to gain the most solar yield possible.

Orientation and Collector Type:
As written above, the collector orientation, tilt and type can be chosen to optimize the fraction of solar energy converted to heat. This effect can be studied for example by using the steady state version of the solar-keymark equation below using the parameters η_0, a_1, a_2:

[1] Note that this does not mean that these parts are minor details or unimportant for optimization. Instead, it is only a simplification in the design space that is often made for dimensioning systems. For example, adding the heat exchangers overall-heat-transfer-coefficient as parameter to the design space is rarely done. The reason is that a good size for this parameter can be derived based on the solar yield only. Thus, the information about a good heat-transfer-coefficient (to be used at the heat exchanger) can be deduced solely based on one of the other dimensions of the design space. As a result, the dimension is sufficient to describe the characteristics of the system.
[2] In fact, it is sublinear because more and more heat losses occur if more collectors are used for the same demand.

$$\eta_{col} = \eta_0 - a_1 \frac{\Delta T}{G} - a_2 \frac{\Delta T^2}{G} \qquad \Delta T = T_m - T_{amb} \qquad T_{col} = \frac{(T_{inlet} + T_{outlet})}{2}$$

Where η[%] denotes the efficiency of the collectors given the solar keymark-parameters η_0 [%], a_1 [W/m².K] and a_2 [W/m².K²] which describe the efficiency and first and second order heat losses of the collector depending on the temperature. The equation above uses instantaneous values for the inlet T_{inlet} [°C] and outlet temperature T_{outlet} [°C] of the collector and the ambient temperature $T_{amb}[°C]$. Depending on the use-case, it is recommended to use more accurate quasi-dynamic testing models, which are described for example in (Kovacs, 2012) or (Ohnewein, et al., 2020) and incorporate the incidence angle modifier.

Together with the total radiation on the collector surface G [W/m²] and the ambient temperature T_{amb}, the expected annual energy production Q_{sol} [Wh] can be estimated:

$$\dot{Q}(t) = A_{col} \cdot G(t) \cdot \eta_{col}(t)$$

$$Q_{col} = A_{col} \cdot \int_{year} G(t) \cdot \eta_{col}(t) \; dt$$

Where $\dot{Q}(t)$ [W] denotes the instantaneous solar power and A_{col} [m²] is the collector area. With this equation it is possible to evaluate which collectors have the best attributes for performing in a certain kind of environment by setting the parameters according to the collector-certifications and comparing the results. It is also possible to calculate the optimal orientation and tilt of the collectors with the same equation. Interesting orientations are - for example - the one with the most solar radiation on the collector surface for the whole year, or alternatively orientations at which the radiation is best aligned with the expected consumer demand.

Expressions for calculating the expected radiation as well as guidance to calculate the radiation on a tilted surface based on the horizontal irradiation can be found in detail in (Duffie & Beckman, 2006). However, often tools like Meteonorm or measurements from climate stations are used to extract values for the ambient temperature and irradiation.

Shading:

Other internal optimizations include the prevention of shading. Again (Duffie & Beckman, 2006) provide equations to estimate the fraction of the collector area that is shaded by internal shading. When optimizing, the system designer thus must balance the additional gain of placing collectors more densely with the increasing losses through shading. There are similar methods to calculate shading due to large object in the periphery as well.

Hydraulics and Control Strategy:

For optimizing the hydraulics and the control strategy a more elaborate strategy is needed as more and more details need to be considered. However, simple heuristics can be applied during simulations to get approximations for feasible system designs. For example, pumps can be started when radiation exceeds about 300 W/m², or when the collector temperature exceeds a certain threshold. The speed of the pump can be steered to produce temperatures that are just high enough for the consumer, but low enough such that the heat losses are as small as possible. The flow speed of the fluid should be around 1-3 m/s (this varies for large pipe dimensions). Hydraulic aspects, piping and similar topics, however, must be studied based on the special requirements of the consumer and the available landscape.

Heat Losses:

Heat losses of pipes Q_{losses} [Wh] due to circulation can be estimated by the equation below based on (Quaschning, 2015):

$$Q_{losses} = U' \cdot l \cdot t \cdot \left(\mathrm{T}_{\mathrm{pipe}} - T_{amb}\right)$$

Where l [m] is the length of the pipe, t [h] is the duration of the circulation, $\mathrm{T}_{\mathrm{pipe}}$ [°C] is the temperature of the fluid in the pipes, $\mathrm{T}_{\mathrm{amb}}$ [°C] is the ambient temperature and U' [W/m.K] is the heat transfer coefficient. The latter can be estimated by:

$$U' = \frac{2\pi}{\frac{1}{\lambda}\ln\frac{d_i}{d_p} + \frac{1}{\alpha \cdot d_i}}$$

With d_p [m] denoting the diameter of the pipe (without insulation), d_i [m] the diameter of the pipe including the insulation, λ [W/m.K] the thermal conductivity of the insulation and α the heat transition coefficient from insulation to air which can be assumed to be between 10.0 and 15.5 [W/m².K] dependent on the value for U'. In case of a buried pipe the heat transfer coefficient can be estimated based on (Hicks & Chopey, 2012) by:

$$U' = \frac{2\pi}{\frac{1}{\lambda_{ground}} \cdot \cosh^{-1}\frac{2z}{d_i}} \cong \frac{2\pi}{\frac{1}{\lambda_{ground}} \cdot ln\frac{4z}{d_i}}$$

With z [m] denoting the distance between the ground surface and the centre of the buried pipe while λ_{ground} [W/m.K] denotes the thermal conductivity of the soil. In addition, the T_{amb} [°C] now denotes the surface temperature of the ground. The formula can only be used when the length of the pipe l is much larger than z.

Hence, the costs for better insulation can be compared with the additional power gain due to less heat losses and the thickness of the insulation chosen accordingly. In addition, heat losses during night might be modelled via the a_1 and a_2 parameter of the solar keymark equations.

External Dependencies:

The most important boundary condition for the solar collector circuit is the consumer demand, weather conditions, and the return and flow temperatures from other *modules*. Often, a requirement must be met that the solar flow temperature is above a certain threshold such that the heat can be supplied to the heating grid. This, however, can also be achieved by reheating with external heating. Apart from that, there might be minima and/or maxima for energy supplied to the grid for certain periods.

Limits:
The natural limit of scaling the solar collector circuit is when no more space is available for mounting the collectors. In this case, heat generation can only be optimized but not scaled arbitrarily anymore.
Another important limiter is too-low heat consumption leading to high collector temperatures. If stagnation with temperatures above 120°C occurs, the system may get damaged beyond repair. For prevention either the heat consumption must be increased, energy must be stored, or stagnation prevention must be applied (see IEA Task 49 fact sheet (Frank, et al., 2015)).

Heat Storage

The heat storage *module* consists of the heat storage tank including the inlets and outlets for storing and extracting the thermal energy. The purpose of the heat storage is to conserve energy when it cannot be used by the consumer right away. As such, the heat storage can be scaled by their volume, while insulation and dimensions of the storage impacts the ability to keep heat losses to a minimum.

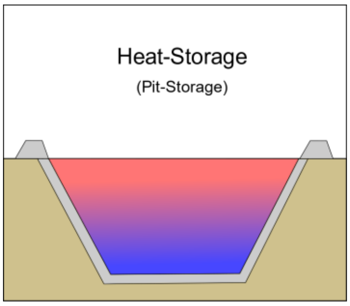

Figure 5: Sketch of a pit storage as an example-technology for storing heat.

Even though the technology is different and simulation models differ, pit storages are considered equally with puffer storage tanks and other technologies as heat storages in this fact sheet, if not stated otherwise. This is because the purpose, scaling and limits are similar in all cases. The interested reader is referred to SHC IEA Task 45 factsheet 45.B.1 to 45.B.3 (https://task45.iea-shc.org/fact-sheets) for more information about large scale storages. In addition, guidelines for materials and construction for seasonal storages will be available at https://task55.iea-shc.org/fact-sheets.

Scaling:
As described, the main function of the heat storage is to store the energy which is produced but not needed yet. Thus, the storage capacity of the heat storage - which is proportional to the volume - is the important property that needs to be scaled.

Optimization:
The volume of the heat storage can be used to scale the system, as this makes it possible to store more energy in the tank. However, if the energy is needed at a later time, the heat stored is naturally exposed to heat losses. The heat losses of a conventional heat storage tank can for example be calculated based on (Quaschning, 2015) separating the tank into a cylindric and top/bottom part:

$$\dot{Q}_{loss} = \dot{Q}_{loss}^{cy} + 2\,\dot{Q}_{loss}^{cap}$$

The loss through the cylindric part of the tank can be calculated similar to the pipes with:

$$\dot{Q}_{loss}^{cy} = U' \cdot l_{cy} \cdot (T_{Hst} - T_{amb})$$

With the height of the cylinder l_{cy} [m], the temperature in the storage T_{Hst} [°C], the ambient temperature T_{amb} [°C] and the heat transfer coefficient U' [W/m.K]. The latter can be calculated by:

$$U' = \frac{\pi}{\frac{1}{2\lambda}\ln\frac{d_o}{d_i} + \frac{1}{\alpha \cdot d_o}}$$

Where λ [W/m.K] is the thermal conductivity of the insulation, d_o [m] is the outer diameter of the tank including the insulation and d_i [m] is the diameter of the tank and α [W/m².K] is again the heat transition coefficient between storage and ambient air.
Similarly, the losses through the caps can be calculated based on (Quaschning, 2015) by:

$$\dot{Q}_{loss}^{cap} = U \cdot A_{cap} \cdot (T_{Hst} - T_{amb}), \qquad A_{cap} = 2\pi \cdot h \cdot r$$

Where A_{cap}[m²] is the area of the cap, calculated with the curvature radius of the storage cap r [m] and h [m] the height of the cap. The heat transfer coefficient U[W/m².K] is calculated by considering the heat transition from storage to insulation $\alpha_1 \sim 300$ [W/m².K], from insulation to air α_2 [W/m².K] and the thermal conductivity of the insulation λ [W/m.K] combined with the thickness of the insulation s [m] with:

$$U = \frac{1}{\frac{1}{\alpha_1} + \frac{1}{\alpha_2} + \frac{s}{\lambda}} \qquad \alpha_2 \simeq \begin{cases} 2.3 \left[\frac{W}{m^2.K^2}\right] \cdot \sqrt[4]{T_{hst} - T_{amb}} & \text{if on top} \\ 1.7 \left[\frac{W}{m^2.K^2}\right] \cdot \sqrt[4]{T_{hst} - T_{amb}} & \text{if at bottom} \\ 2.2 \left[\frac{W}{m^2.K^2}\right] \cdot \sqrt[4]{T_{hst} - T_{amb}} & \text{if positioned sideways} \end{cases}$$

As the equations above show, the heat loss is dependent on the insulation that is used. However, also the diameter of the tank affect heat loss as different choices changes the surface exposed to the ambient temperature.
Naturally, the model for the calculation must be adapted accordingly if other shapes are used. Apart from that, thermal stratification can be used to optimize the usable energy stored inside the tank. In this case the fluid is layered inside the tank with high temperatures at the top. This can be modelled by dividing the storage into multiple sections and calculating the heat flow and temperatures for each of the sections individually. For construction, multiple input- and output pipes can be placed in strategic positions in order to properly load the heat storage according to the temperature levels. Good control strategies can then make use of them by controlling the flow of the fluid with valves.

In the case of pit storages, the models for calculation differ. In this case the formula must be adapted for the heat transferred from the storage to the storage walls and further to the ground, by using the corresponding thermal conductivities and altering the formula according to the storage shape. In addition, the heat capacity of the ground next to the storage should be considered as well.

External Dependencies:

Heat storages are used together with modules used for heat generation. Thus, they highly depend on the temperatures and heat provided and extracted by them. Plus, the minimum return temperature at the extraction side can be considered the lower limit of the heat storage temperature.

Limits:

One factor that is a lower bound on the energy capacity of the heat storage is the minimal and maximal temperature of the heat storage. For typical storage tanks the temperature inside the tank should not exceed 110°C. The tank size must thus be at least large enough to store surplus heat without reaching temperatures higher than this maximum temperature, introducing a lower bound for the storage tank volume. In contrast, if all the produced energy can be used right away, there is no need to store the energy in a tank. In this case the heat storage is unneeded and can be excluded from the system.
If the demand for storage heat is very high, huge storage tanks need to be installed at the system. At this point, standard storage tanks might be too expensive, posing an upper bound for the system scaling. In this case, technologies like borehole storages or water pit storages might be used. However, if more energy is stored for longer periods of time the heat is subject to higher heat losses. Another factor ultimately limiting the volume of the heat storage is the available space for the storage.

External heating

The main purpose of the external heating module is to provide additional heat to the system. It can be applied to meet the customers energy demand if the solar heating system is not able to perform without it, or to boost medium temperatures to even higher ones. Alternatively, it could also be used to power a heat pump. It may consist of a biomass boiler, electric boiler, or any other device producing heat from different energy sources. With external heating, heat can typically be produced exactly when it is needed, without restrictions or dependencies like the weather in the case of the solar collector circuit module. As a drawback the primary energy is often more expensive than using the solar energy or is highly correlated with carbon emissions. Typically, external heating is already installed at the district heating grids before solar heating systems have been considered.

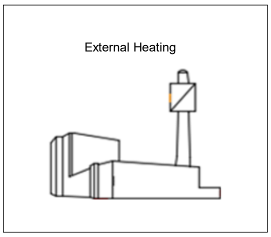

Figure 6: Sketch external heating.

Scaling:

The external heating scales by the power capacity of the device used.

Optimization:

The performance of the external heating is often given by specifying the efficiency of converting primary energy to heat. With this factor also the costs and CO2 emissions can be calculated. Other potentials in optimization is in considering starting and shutdown behaviors and optimize the control strategies. In addition, the operating temperatures often influence the efficiency of the external heating.

Dependencies:
Similar to the other modules that are used for heat generation, the external heating is dependent on the consumer demand and the return temperature of other modules. However, there is typically no dependency on the weather often making this a great addition to solar heating systems if the power consumption is high during periods with low solar radiation.

Limits:
Well-designed solar heating systems are often cheaper when considering sufficiently long periods. In addition, they are not dependent on changes in heat prices and their carbon emissions are considerably lower. In contrast, the main limit of external heating modules are costs and carbon emissions. Apart from that, the maximum heat demand of the consumer and the heat production of other modules induces a limit to scaling the external heating.

Absorption Heat-Pump

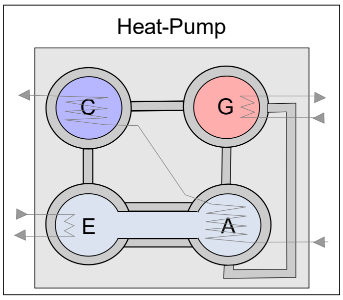

Figure 7: Sketch of heat pump.

In district heating applications heat pumps can be used for heat generation using even low storage temperatures. For this setup, the heat pump is driven by external heating while the fluid from the storage is used at the low temperature evaporator circuit. As a result, the district heating temperature in the absorber and condenser circuit is raised to the desired flow temperature, while the storage temperature gets cooled down at the evaporator. This has three beneficial effects: First, low temperatures in the storage can still be used for generating useful heat for the consumer. Second, the storage temperature gets cooled down, further increasing the maximum temperature difference of the storage. Thus, storages with less volume can store more energy and the collector efficiency raises due to cooler return temperatures and thus less heat losses. Finally, also the heat losses in the storage are reduced due to the reduced temperatures.

Scaling:

Absorption heat pumps for large scale solar thermal applications are often designed specifically based on the desired temperatures. Typically, the internal mechanism inside the machines is optimized on these temperatures by the manufacturer. As each heat pump differs based on these considerations, prediction and simulation models are hard to generalize with good results. Instead of dynamic performance measures, the coefficient of performance is often provided by the manufacturer for a specific choice of temperatures and energy intake and outtake. Predicting the dynamic operation of heat pumps and their optimization is non-trivial and currently studied in research projects (i.e. FFG project HPC 'Modellbasierte Regelung von Absorptionswärmepump-Anlagen'). In feasibility, the temperatures are thus often considered steady-state and the *module* is dimensioned based on the nominal heat pump capacity.

Dimensioning

In the last section the *modules* have been described. Here, it is discussed which methods exists to evaluate feasible regions in the design space, which was introduced in the first section. In other words, how to choose the dimensions of all the *modules* appropriately.

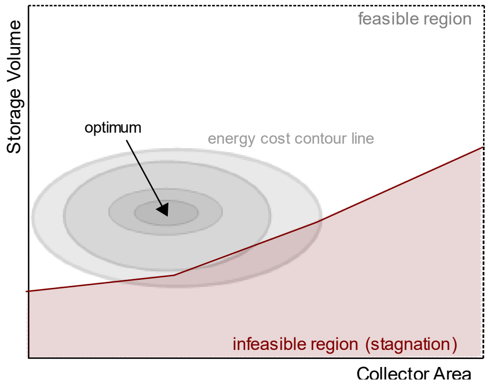

Figure 8: Sketch for 2D design space for heat storage and collector circuit (drawn with Inkscape).

In principle, this section can be separated into two parts:
First, it is evaluated which configurations of the design space can be used to provide **energetically** reasonable system designs. These considerations allow to rule out infeasible designs (see red-colored area in Figure 8). Alternatively, methods recommend specific design choices instead.
Second, the economic benefits of the feasible designs need to be analyzed in order to identify the best **economical** solution for the customer. To do so, cost functions for each *module* dimension can be defined to calculate the costs for a configuration. Combined with the computed energy yield from the energetic considerations the economically best design can be found. For example, in Figure 8 energy-costs are visualized by gray contour curves, while the optimum design is at their center.

Energetical dimensioning

Methods discussed here can be used to get a rough idea about which *module* configuration results in designs with high amounts of usable heat, lying in feasible regions of the design space. Naturally, the discussed methods vary in simplicity and accuracy - from simple rule-of-thumb methods to detailed simulations – and are usable in different cases. These methods typically return the amount of usable energy that can be produced annually, but do not incorporating costs into the consideration. The list also contains methods that are not recommended for district heating – as noted in the discussion of the methods. However, they were included nonetheless, in order to show which methodologies for designing systems generally exist and why some are not usable for designing solar thermal systems for district heating yet.

Rule-of-thumb methods:
One type of methods for choosing potential system designs are simple rule-of-thumb methods. For this type of method, the dimensions of the modules are estimated based on experiences of system designers or empirically found through running many calculations. An example for a rule-of-thumb method for pre-dimensioning collector circuit and heat storage for solar process heat can be found in (Heß & Olivia, 2010) – see below. Though this method is used for solar process heat only, it shows how rule-of-thumb methods work in principle. These methods are generally very useful for first estimations or for doublechecking simulation results. Using rule-of-thumbs or benchmarks is extremely helpful because results are obtained exceptionally fast. However, authors typically suggest to not using these methods without detailed simulations for further study. The reason is that small differences in the boundary conditions (i.e. demand, or weather) may result in drastically different optimal designs and thus details play a huge role in

dimensioning the system. With this, using benchmarks and rule-of-thumb estimations is typically not accurate enough, but only gives rough estimates.

Method from (Heß & Olivia, 2010)**:**

The method uses the energy demand of the consumer to estimate the size of the solar collector circuit and the dimension of the heat storage for solar process heat applications. Other components are not considered. The desired size of the solar collector circuit module A_{col} [m²] is estimated based on the energy demand Q_d [kWh] of the consumer and the available area A_{area} [m²] by:

$$A_{col} = \begin{cases} \frac{A_{area}}{2.5} & \text{if } \left(\frac{A_{area}}{2.5} \cdot 500 \left[\frac{kWh}{m^2}\right] < 60\% \cdot Q_d\right) \\ 40\% \cdot \frac{Q_d}{500 \left[\frac{kWh}{m^2}\right]} & \text{else} \end{cases}$$

The formula thus suggests using as much of the available space as possible if the estimated yield is lower than 60% of the demand. If this is not the case, the collector area should be sized such that approximately 40% of the demand is covered. Note that it is assumed that the area where the collectors are mounted is flat – if they are placed on tilted structures like roofs the factor 2.5 can be dropped according to the authors.
The approximated volume $V_{storage}$ $[l]$ of the heat storage can then be estimated based on the calculated collector area, with the formula[3]:

$$V_{HSt} = x \cdot A_{col}, \qquad x = \begin{cases} 50 \left[\frac{l}{m^2}\right] & \text{for northern europa} \\ 80 \left[\frac{l}{m^2}\right] & \text{for southern europa} \end{cases}$$

While the calculation is very simple and results can be obtained very fast, the authors of the method suggest using these values only as starting point for further evaluation. Final designs should be validated by detailed simulations.

A much more detailed and more flexible rule-of-thumb method useable for district heating can be found in (Nielsen & Battisti, 2012). It covers the design of solar heating systems based on estimations for the collector area and storage size based on the weather condition and demand and provides estimates for costs. However, as noted by (Mangold & Deschaintre, 2015) there exist no rule-of-thumb for seasonal thermal energy storages (STES) yet and detailed studies for interactions with STES have to be carried out. Nevertheless, lots of pre-feasibility tools (see section Available Tools) incorporate rule-of-thumb methods for their calculations due to the benefits noted above.

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[3] Please mind that this method is targeting process heat applications and differs when other types of applications or higher solar fractions are considered.

Short-Cut Simulations:

For this type of methods, simulation-like approaches are used to calculate energy yields dynamically. However, simplifications are made in order to simplify the calculation. For example, one could use representative days for each month for the simulation to decrease computation time instead of calculating each day of the year in detail. Other methods might instead use simplified models of components and ignore some of the components dependencies and optimization parameters in order to first get a rough idea about the system design. The benefits are typically speed-ups in computation time and more importantly less domain knowledge requirements, as well as less time investment for doing the configuration of the simulation. However, using simplifications naturally lead to less accurate results. Nevertheless, the reduced time-requirements are especially beneficial when multiple configurations of the design space are considered.

One of such simplified methods is described below. It tries to decouple the calculation of the *modules,* always relying on already calculated values for determining "good" dimensions for the next *module*. The proposed method should show how simplifications can be introduced to simplify calculations, however, is not yet fully validated:

Simplification:

As a first step the heat demand of the district heating grid and the weather conditions (for example from Meteonorm-data or measurements from weather stations near the system site) needs to be known. Given a collector area A_{col} [m²] and assuming some temperatures for the inlet and outlet of the collector, the solar power can be calculated based on the Solar Keymark equation (using parameters η_0, a_1 and a_2 only):

$$\dot{\bar{Q}}_{col}(t) = \eta_0 \cdot G(t) - a_1 \cdot \Delta T(t) - a_2 \cdot \Delta T(t)^2$$

$$\Delta T(t) = T_{col}(t) - T_{amb}(t)$$

$$T_{col}(t) = \frac{T_{inlet}(t) + T_{outlet}(t)}{2}$$

With $\dot{\bar{Q}}_{col}$ [kW/m²] denoting the specific solar power and η_0 , a_1 and a_2 denoting the parameters of the solar key mark certification. The total solar power from the collectors can simply be calculated by multiplying the specific power with the given collector area A_{col}:

$$\dot{Q}_{col} = \dot{\bar{Q}}_{col} \cdot A_{col}$$

And annual specific solar yield and annual solar yield can be calculating by integrating the solar power for the whole year:

$$Q_{col} = \int_{year} \dot{Q}_{col}(t)\, dt$$

$$\bar{Q}_{col} = \int_{year} \dot{\bar{Q}}_{col}(t)\, dt$$

In contrast to what the equations might suggest, the specific solar power $\dot{\bar{Q}}_{col}(t)$ is not independent of the collector area. This is because a larger number of collectors will lead to more energy produced and – if not extracted immediately from the system – will increase the temperature in the collectors. This way, temperatures $T_{col}(t)$ can typically only be calculated dynamically using the results of the previous timestep as input:

$$\frac{dT_{col}}{dt} = \frac{1}{C} \cdot \left(\dot{\bar{Q}}_{col}(t) \cdot A_{col} - \dot{Q}_{out}(t)\right)$$

With C the heat capacity of the collectors and $\dot{Q}_{out}$ the energy which is extracted from the solar collector circuit. The problem is that by changing the collector area a new simulation must be carried out because of this dependency. However, we can eliminate the dependency of the collector area A_{col} if we assume that all the energy is always extracted from the system at each timestep:

$$\dot{Q}_{col}(t) = \dot{\bar{Q}}_{col}(t) \cdot A_{col} == \dot{Q}_{out}(t)$$

Leading to:

$$\frac{dT_{col}}{dt} = \frac{1}{C} \cdot \left(\dot{Q}_{col}(t) - \dot{Q}_{out}(t)\right) = 0$$

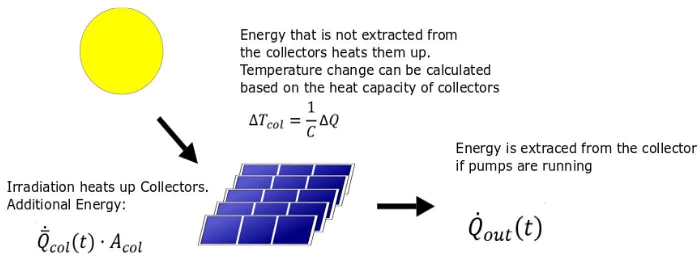


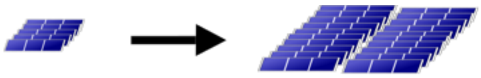
Figure 9: If energy is not extracted from the solar circuit, the collector heats up accordingly. As a result, the collector temperature does not change if the same amount of energy is extracted and introduced to the solar collector each timestamp.

What is left is choosing appropriate values for the initial collector temperature, as these values will not change anymore:

$$\frac{dT_{col}}{dt} = 0 \quad \rightarrow \quad T_{col}(t) = T_{col}(0) = \frac{T_{inlet}(0) + T_{outlet}(0)}{2}$$

For example, the collector inlet temperature T_{inlet} can be chosen to be the temperature provided by the consumer while for the collector flow temperature T_{outlet} the desired (demand) temperature can be used. In general, this simplification is not true as collectors will be much cooler during sunrise and sunset (heating up and cooling down) and may be way higher in cases of too low demand, or too small storage capacity and too high irradiation. Thus, the simplification made here is that all the energy is assumed to always be extracted from the solar heating circuit immediately. By assuming so, the collector temperature stays constant all the time, greatly simplifying the calculation.

The calculation of the solar yield for all timestamps can now be done in parallel, as temporal dependencies have dropped out. As a result, this makes the calculation of the specific solar yield $\bar{Q}_{col}$ independent of the collector area (see **Figure 10**). Naturally, the results from this simplification can never achieve the accuracy of full-fledged simulations, however, can be used as first guess.



	Calculation	Scaling
Simplified:	Estimate Temperatures Calculate specific solar yield based on irradiation, collector type and ambient temperature (in parallel)	Simply multiply according to increase in collector area. Calculate other modules later.
Simulation:	Calculate temperatures, energy, volume-flows, etc. by modelling all components of the system including deciding on dimensions for other modules.	Do whole calculation again with updated collector area and rethink dimensions of other module-dimensions. Simple multiplication not possible because volume flow, temperatures, start up pumps, dynamically change.

Figure 10: Comparison to simulation to show the effects of simplification.

Scaling the solar collector circuit module:
With the assumption above the solar yield Q_{col} now scales linearly with the collector area[4]:

$$Q_{col} = A_{col} \cdot \bar{Q}_{col}$$

That means that the yield with different collector sizes can be estimated simply by multiplying the calculated values for $\bar{Q}_{col}$ accordingly. If a specific solar fraction is desired, it can be roughly estimated, too, by:

$$Q_{col} = Q_d \cdot f_{solar} \quad \rightarrow \quad A_{col} = \frac{Q_d \cdot f_{solar}}{\bar{Q}_{col}}$$

Where Q_d [kWh/a] has been used to denote the consumer demand and f_{solar} [%] is the desired solar fraction. Alternatively, one can simply try multiple values for A_{col} and compare the results.

Not included in this calculation are the losses from shading and losses in the solar collector loop. Such factors can either be added based on benchmarks or more accurately calculated based on used temperatures for inlet and outlet. In addition, the collector efficiency calculation could be made more accurate by using the quasi-dynamic-testing parameters

[4] Without that constraint this would have not been the case as the collector temperature is dependent on the collector area, too. For example, if heat demand is limited but a lot of energy is generated the collector is heating up because the heat is not extracted. The effect is amplified by the collector area, as the heat is accumulated from the power production of previous timestamps. In fact, this can also be seen in simulations where at some point the solar yield scales sub-linearly with the collector area. This is because the efficiency of the collector decreases for higher temperatures due to increased heat losses.

instead of the steady state parameters or at least by incorporating the incidence angle modifier.

Scaling the heat storage module:

The assumption used above states that all energy is extracted from the solar circuit. However, in real application this is hardly the case for large scale applications as demand and irradiation are not aligned with each other. For district heating for example, winter demand is much higher than during summer when irradiation is at its maximum and daily demand peaks might not coincide with high irradiation (see Figure 11). Thus, excess energy must be stored in order to fulfil the assumption and prevent stagnation. This consideration can be used to define an optimal storage volume for a chosen collector area size. The heat store module thus can be sized according to this criterion, by calculating how much maximum energy needs to be stored at some time. The surplus power $\dot{Q}_+$ [kW] that cannot be used instantaneously can be calculated by comparing the solar yield $\dot{Q}_{col}$ [kW] and the consumer demand $\dot{Q}_D$ $[kW]$ at each timestamp:

$$\dot{Q}_+(t) = \dot{Q}_{col}(t) - \dot{Q}_d(t)$$

However, the storage does not only need to store the surplus power, but all the energy added up to this point as well. Thus, the storage must be dimensioned based on the accumulated heat:

$$Q_{HST}(t) = \max\begin{pmatrix} 0 \\ Q_{HST}(t-dt) + \dot{Q}_+(t) \cdot dt \end{pmatrix}$$

In this equation dt denotes the difference between one timestep and the next one – typically based on the frequency of the weather data. The lower part of the equation denotes that surplus energy $\dot{Q}_+ \cdot dt$ is added to the energy Q_{HST} that is already stored in the storage. In other words, if there is surplus energy it will be stored in the tank. If the surplus energy is however negative, energy is extracted from the storage. Because the energy in the storage cannot be negative, the maximum function ensures that no energy can be extracted if the storage is empty.

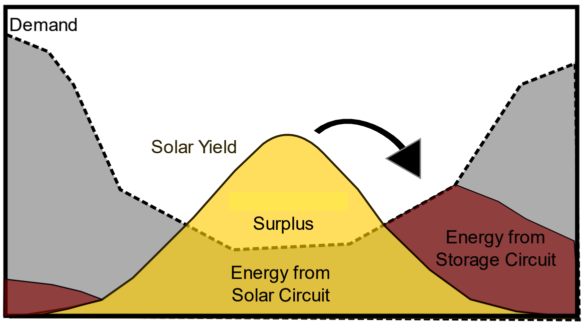


Figure 11: Sketch. Surplus energy that cannot be used at that time is stored in the storage until needed.

Note that here another simplification was made as heat losses and stratification are not considered in the calculation of the accumulated energy. This can be however accounted for by modifying the equation accordingly. This can be either done with rule-of-thumb approximations – for example constant percentage of losses each timestamp – or with modelling the heat losses dynamically with equations described in the heat-storage module section. Another factor that must be taken into account is that with this setup the storage starts completely empty. If at the end of the year the storage is non-empty, the calculation should be repeated with new initial energy, until the energy content of the storage at the end of the year matches with the start of the year.
For properly dimensioning the storage the volume V for storing this much energy can be calculated by:

$$V = \frac{\max\big(Q_{HST}(t)\big)}{c_p \cdot \Delta T}, \qquad \Delta T = (T_{outlet} - T_{inlet})$$

Here, the heat capacity c_p [kWh/m³.K] is dependent on the fluid (typically water) and the temperature difference ΔT can be estimated by using (again) the desired flow and provided return temperature of the heating grid. Put in other words, this equation describes that the energy storage minimum and maximum energy is limited by the given minimum and maximum allowed temperatures. Thus, the volume must be chosen such that the maximum accumulated surplus energy can be stored with the given temperature difference ΔT.

Scaling the external heating:
With the solar yield already calculated the missing energy to satisfy the consumer demand must be provided by external heating (grey parts in Figure 11).

$$\dot{Q}_{ext}(t) = -\frac{1}{dt}\min\begin{pmatrix} 0 \\ Q_{HST}(t-dt) + \dot{Q}_{+}(t)\cdot dt \end{pmatrix}$$

Scaling heat pump:
Heat pumps can be used at the solar heating system for lowering the temperatures of the storage below the heating grid return. As discussed in the *module* section, this is done by using external heat as driving source for the heat pump and using the energy in the storage for the evaporator circuit. As a rule of thumb, the decrease in the minimum temperature can be approximated by 30 K:

$$\widetilde{T_{inlet}} = T_{inlet} - 30°C$$

As a direct result, the heat storage can store more energy as a higher temperature difference can be reached:

$$\tilde{V} = \frac{max\big(Q_{hst}(t)\big)}{c_p \cdot \Delta\tilde{T}}, \quad \Delta\tilde{T} = \big(T_{flow} - \widetilde{T_{ret}}\big)$$

Thus, money can be saved by using a smaller storage. However, if the temperature in the storage is below T_{ret} the heat-pump must be used to supply the energy to the grid. The corresponding energy can be calculated by comparing the energy in the tank at T_{ret} (i.e. empty tank if no heat pump) with the energy in the tank with temperatures at $\widetilde{T_{ret}}$ (i.e. empty tank if heat pump is used):

$$Q_{HTP} = \tilde{V} \cdot c_p \cdot \left(T_{ret} - \widetilde{T_{ret}}\right) = \tilde{V} \cdot c_p \cdot 30\ [K]$$

If the energy of the storage is below this value, the heat must be extracted by the heat-pump. However, the amount of energy that can be extracted at a time is limited by the demand and more importantly by the capacity of the heat-pump.

Assuming a seasonal thermal storage the energy content of the storage has its maximum in late summer while the storage gets drained over winter due to the high demand. Thus, there is one cycle of completely filling and extracting the energy from the storage. If the energy cannot be completely extracted from the storage due to too low heat pump capacities, the energy content increases and the conditions for calculating $\tilde{V}$ are not valid anymore. Thus, for keeping the storage volume constant, the heat-pump maximum capacity must be chosen with a heat capacity that ensures that all energy Q_{HTP} can be extracted. Thus, we must choose the capacity C_{HTP} accordingly:

$$\text{select } C_{HTP} \text{ such that } \quad \rightarrow \quad 0 = Q_{HTP} - \int \dot{Q}_{HTP}(t,\ C_{HTP})\, dt$$

looking at which situations the heat pump can be used:

$$\dot{Q}_{HTP}(t) = \max \begin{cases} 0 & \text{if } Q_{hst} > Q_{HTP} \\ 0 & \text{if } \dot{Q}_+ > 0 \\ \min\left(C_{HTP},\ |\dot{Q}_+|\right) & \text{else} \end{cases}$$

The upper term of the second equation means that energy is not supplied via heat pump if the storage is full enough to supply energy directly. In addition, the middle part ensures that no energy is used from the heat-pump if it can be supplied by the solar circuit. Finally the min() function in the lowest term ensures that the energy extracted cannot exceed the demand or the heating capacity of the heat pump.
In the equation above, the power is added up and demands that C_{HTP} is set such that all the energy Q_{HTP} is be extracted by the heat-pump exactly once per cycle. As this equation cannot be solved for C_{HTP} directly, methods like the bisection technique can be applied in the range of $C_{HTP} \in \left[0, max\ \dot{Q}_+(t)\right]$ to find the optimal value of the heating capacity C_{HTP}.

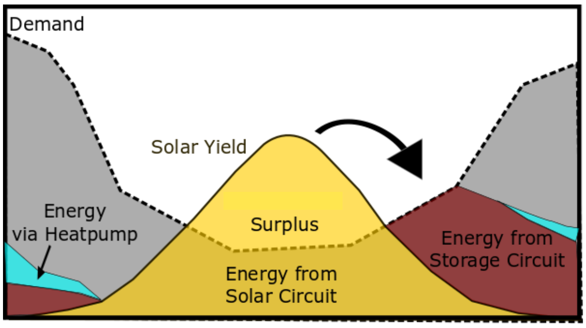


Figure 12: Sketch. Additional energy can be extracted from the storage via the heat pump. In addition, more solar yield can be generated due to lower operation temperatures.

In addition, the amount of external energy needed must be updated as the heatpump is driven by external heat which concludes the estimation of all module dimensions:

$$\widetilde{\dot{Q}_{ext}} = \dot{Q}_{ext} + \frac{C_{HTP}}{COP_{th}}$$

This method describes a feasible hypersurface in the design space, for which all energy is extracted from the solar circuit. In real applications, this restriction is often too strict and slightly smaller storages can be used for most systems. However, initial starting points for simulations can be found with this kind of methods. The estimations can be made more precise by altering the simplifications made. For example, the temperatures at the collectors can be set dependent on the energy in the heat store or dependent on daily, monthly or yearly patterns. In addition, temperatures could be calculated for the estimation of heat losses in pipes and the heat storage or shading effects can be applied in detail. Plus, the heat pump model used in the above consideration only covers the reduced heat in the storage. However, also the efficiency of the solar circuit rises due to the lower inlet temperatures.

Another short-cut simulation for the determination of the design space of heat storage and collector area including external heating can be found in (Kulkarni, et al., 2007) using a fully mixed model for the heat storage and assumes steady state temperature profiles.

In addition, independently of this factsheet (Narula, et al., 2020) recently published a shortcut method describing a simulation method for district heating systems with a seasonal thermal storage, solar collectors, heat pump and boiler. The authors use predefined sizes for the storage size and the collectors which are fixed by the consumer demand and the available area respectively. They not only provide energetical results by computing hourly energy flows, but also consider costs and carbon emissions in their comparisons (see section economical dimensioning in this factsheet).

Simulation-based methods:

In simulation-based methods designs are studied by using detailed simulations of proposed system, for example with software like TRNSYS (Duffie & Beckman, 2006) or Modelica (Modelica Association, 2017). To derive the best possible layout, often multiple simulations with varying *modules*-dimensions are performed. By observing the changes of the energetic results and combining them with the economic cost functions, potential solutions can be found and studied in detail. While this method offers good accuracy, the drawback is that they need high domain-knowledge and extensive care to properly model the system. Because of the time investment for preparing and running the simulations, this approach is often used only after potential designs have already been derived with other methods. Nevertheless, when using good models, the results of simulation-based approaches are very accurate and give dynamic information about the system. Thus, important insights may be discovered which might be neglected by other methods. This is the reason why most companies engaged in solar thermal engineering recommend using simulations for study the proposed system design (Design Handbook IEA Task 45) (Heß & Olivia, 2010; Duffie & Beckman, 2006).

Economical dimensioning

While the energetical dimensioning typically is able to tell which system layout gives the most usable energy, also the costs of the systems have to be checked in order to guarantee that the best economical solution has been found. To do this, the costs of each *module* configuration must be known. In this case (for example) the minimum heat generation price can be found, when used together with the energetic results. For this purpose, cost functions for components have been described in (Große, et al., 2017).
Naturally there are also other objectives that can be incorporated into the consideration beside costs versus energy production. For example, (Franco, 2020) expanded the objective function by introducing a penalty factor for the irreversibility of the heat generation. This was done in order to highlight the benefits of renewable solar energy in contrast to using fossil fuels.
An example of how to incorporate costs and CO2 emissions in the results can be seen in (Narula, et al., 2020) previously mentioned also in the shortcut-simulation section above.

Available Tools

A list of tools for dimensioning solar systems is available at: https://www.solar-district-heating.eu/en/tools/, described in fact sheet (Le Denn & Dechaintre, 2017).They are intended as a first quick estimation of the design parameter and provide energetic and economic results. Most of them use rule-of-thumb methods while some use short-cut simulation methods on a monthly basis.
In addition to the tools described above, the research project OptEnGrid (https://projekte.ffg.at/projekt/1822013) is currently focusing on developing an optimum-based investment decision support software, that allows to determine the optimal supply technology mix for a given application. In contrast to typical simulations, the optimum-based approach results in estimation for costs (levelized costs of energy) and energy yield, but automatically sizes the components to guarantee the least CO2 emissions and/or least energy costs (€/MWh). Additionally, it allows to model a wide range of technologies (around 13 energy supply and storage technologies, including cross sectoral synergies) and economic and political drivers, such as CO2 taxes.

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Appendix A

Table 1: list of used abbreviations and symbols.

Symbol	Unit	Description
η_{col}	%	Effective collector efficiency
η_0	%	Solar key-mark-parameter for collector efficiency
a_1	W/m².K	Solar key-mark-parameter for first order heat losses at collector
a_2	W/m².K²	Solar key-mark-parameter for first second heat losses at collector
a_5	kJ/K.m²	Solar key-mark-parameter for the effective thermal capacity of the collector.
T_{amb}	°C	Ambient temperature
G	W/m²	Radiation total on collector surface
T_m	°C	Collector mean temperature
dT_m	K	Temperature change of mean collector temperature
ΔT	K	Difference between two temperatures (i.e. ambient temperature and collector temperature)
T_{inlet}	°C	Solar inlet temperature
T_{outlet}	°C	Solar outlet temperature
Q_{col}	Wh	energy production (per year, if not otherwise specified)
$\dot{Q}$	W	instantaneous solar power
A_{col}	M²	collector area
Q_{losses}	Wh	Heat losses
U'	W/m.K	Heat transfer coefficient (of pipe/heat storage)
l	m	length (of pipe)
t	h	duration (of the circulation through pipes)
$\mathrm{T_{pipe}}$	°C	Temperature inside pipes
d_p	m	Diameter of pipe (without insolation)
d_i	m	Diameter of pipe (with insolation)
λ	W/m.K	Thermal conductivity of the insulation
α	W/m².K	heat transition coefficient from insolation to air
$\dot{Q}_{loss}$	W	instantaneous heat loss (of heat storage)
$\dot{Q}_{loss}^{cy}$	W	Heat loss of cylindrical part of heat storage
$\dot{Q}_{loss}^{cap}$	W	Heat loss of top or bottom part of the heat storage
l_{cy}	m	Height of cylindrical part of storage
T_{HSt}	°C	Temperature inside storage
d_o	m	outer diameter of the heat storage (with insolation)
d_i	m	inner diameter of the heat storage (without insolation)
A_{cap}	m²	Area of cap part of the heat storage
r	m	curvature radius of the heat storage cap.
h	m	height of the heat storage cap.
α_1	W/m².K	heat transition coefficient from storage tank to insolation (of heat storage)
α_2	W/m².K	heat transition coefficient from insulation to air (of heat storage)
s	m	thickness of insulation (of heat storage)
A_{area}	m²	Available area to build collectors on top

Q_d	kWh	energy demand
V_{Hst}	m³	volume of heat storage
$\ddot{Q}_{col}$	kW/m²	specific solar power
$\bar{Q}_{col}$	kWh/m²	specific solar yield
C	kWh/K	effective heat capacity of the collectors
$\dot{Q}_{out}$	kWh	power extracted from solar circuit
f_{solar}	%	solar fraction. the fraction of the demand which is provided by solar energy
$\dot{Q}_{+}$	kW	surplus power which is extracted from the solar circuit with too less demand
$\dot{Q}_d$	kW	current demand at some time.
Q_{HST}	kWh	Energy content of heat storage at some time.
c_p	kWh/m³.K	heat capacity of fluid
$\dot{Q}_{ext}$	kWh	power that has to be provided by external heating
$\widetilde{T_{inlet}}$	°C	modified inlet temperature of solar circuit
$\tilde{V}$	m³	modified heat storage volume
$\Delta\tilde{T}$	K	modified temperature difference between two temperatures (i.e. inlet and outlet of solar circuit)
Q_{HTP}	kWh	energy that has to be provided by heat pump
C_{HTP}	kW	power capacity of heat pump
COP_{th}	%	thermal coefficient of performance of heat pump
$\widetilde{Q_{ext}}$	kWh	modified energy that has to be provided by external heating