Stahrsolar - Earning more efficiently

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1. Introduction

The goal of Stahrsolar is to present approaches for increasing the attractiveness of smaller solar systems and to examine them for their potential, technical feasibility and market acceptance.

During the planning phase, the aim was therefore to achieve a compromise between the three basic market-relevant elements - economy, environmental compatibility and aesthetics - that would be advantageous for many end customers.
Thus, the installation of the collector on the façade was considered particularly advantageous. In addition to the expected higher yields in the heating season and the lower trend towards stagnation in summer, this was due to the possibility of placing a reflector effectively and to aesthetically enhance the view of the house in an appealing way.

Chemical antifreeze should be avoided for ecological and economic reasons. The cost of producing, operating and disposing of glycol as a carrier medium, for example, drastically worsens the overall ecological footprint of a solar thermal system. The use of pure water with direct connection to the heating system is considered an important feature of a modern solar thermal system for a growing number of customers.

Furthermore was surveyed what awareness and approaches from research and development in the automotive industry could be applied in the solar sector. Here, too, the challenge was to harmonize what was technically feasible with what was advantageous for the customer.

Stahrsolar has already been presented to a wide range of customers, who have found it very appealing.

The three technical pillars of Stahrsolar are presented below.

2. The collector temperature model

2.1. Collector temperatures

By default, the thermal state of the collector is described by at least two measured temperatures - that of the medium entering and that one leaving the collector. When the medium is at rest, these values only provide temperature information at the respective measurement points. The occurrence of larger local deviations within the collector cannot be determined.

Once the flow velocity of the carrier medium is sufficiently high the value of the outlet temperature in particular does become representative for the entire collector and can be effectively evaluated by the control system as global information.

2.2. Motivation ‘Solar start’

The transition from the stationary phase to solar operation - the so-called solar start - is conventionally achieved in two ways:

a) Evaluation of free convection.
   The heated carrier medium rises and ideally reaches the measuring points for the collector outlet. The controller evaluates the amount and/or the rate of change of the temperature and activates the solar pump according to stored threshold values.

b) Arbitrary forced convection
   Via control parameters - for example the time of day or the position of the sun - the solar pump is activated for a short time. If the measured outlet temperature rises above a set point during this so-called purge time, the solar pump remains active. Otherwise it is deactivated. A waiting phase follows, after which the purging process is repeated.

Whether a solar gain is possible can be evaluated by the controller for both approaches after a sufficiently long purging time with a sufficiently high outlet temperature only.

The Stahrsolar collector temperature model has the task of precisely describing the current thermal state of the entire collector in the form of a representative, globally valid temperature value, even when the medium is at rest. On this basis, the controller is able to determine the correct time for the start of the solar earning.

2.3. Motivation ‘Frost protections with pure water as carrier medium’

The advantages of pure water over, for example, a glycol mixture are manifold:

- The lower viscosity lowers the flow resistance and thus the requirement for electrical pumping energy.
- The higher heat capacity leads to a lower temperature and thus lower thermal losses for the same heat input - the same solar radiation.
- The use of heating water also in the collector makes a heat exchanger and the parallel operated pump for the glycol mixture superfluous. The system becomes simpler and less expensive to manufacture, operate and dispose of.
- Glycol is a chemical product that ages depending on the prevailing conditions such as temperature, oxygen content and pressure and therefore needs to be maintained - i.e. replaced. Water does not age and is therefore maintenance-free. No further costs are incurred.
- The production and disposal of glycol is industrially expensive. Pure water is a stable natural compound and can be obtained by simple filter systems. Its ecological balance is therefore already significantly higher from the initial operation of a corresponding solar system.

These advantages are countered by the considerable disadvantage of water freezing at temperatures below 0°C:

- The accumulation of ice crystals on the pipe surface leads to a constriction of the pipe cross-section and even to the complete closure of the pipe. The flow comes to a standstill, which accelerates the icing.
- The specific volume of water increases as the temperature drops. Pipes sealed with ice are subjected to increasing internal pressure as the temperature drops. This can lead to bursting of the pipe and thus to total failure of the system. Especially collectors based on a pipe-in-pipe principle have very small flow cross-sections and thus a high tendency to pipe rupture.

To counteract these disadvantages, there are currently two solutions. If there is a danger of frost, the water is

a) Replaced by air - the collector is emptied
b) Kept constantly in motion and above the freezing temperature by supplying heat.

Based on the Stahrsolar model value, the controller determines the latest safe time to replace the cold water with warmer water. Thereby a minimum collector temperature as well as minimum pumping times shall be guaranteed. Approach b) is significantly optimized in terms of heat and auxiliary energy used.

2.4. Model approach

When the controller has stopped solar operation due to low radiation from the setting sun, the model continues to provide a temperature value.
If the modeled temperature falls below a threshold - for example 4°C - frost protection measures are initiated by the controller.
As the sun rises, the increasing solar radiation leads to an increasing modeled temperature. If this exceeds a threshold value - for example the actual temperature of the heating return - by 2K, the control interprets this as sufficient radiation for the solar yield. The solar operation starts.

2.5. Model principle

When modeling the collector temperature, the principle of heat balance is used. Here, the actual heat of a system results from the sum of the start heat quantity and all inflowing and outflowing partial heat quantities. This approach has proven itself many times in the automotive industry, among others. For example, it is used to determine the temperatures in the clutch or of liquids and gases in the combustion engine.
In the Stahrsolar temperature model, the heat input Q_{zu} into the collector is determined by means of a polynomial formula with fixed and variable coefficients and the measured value of a sensor for the solar radiation.

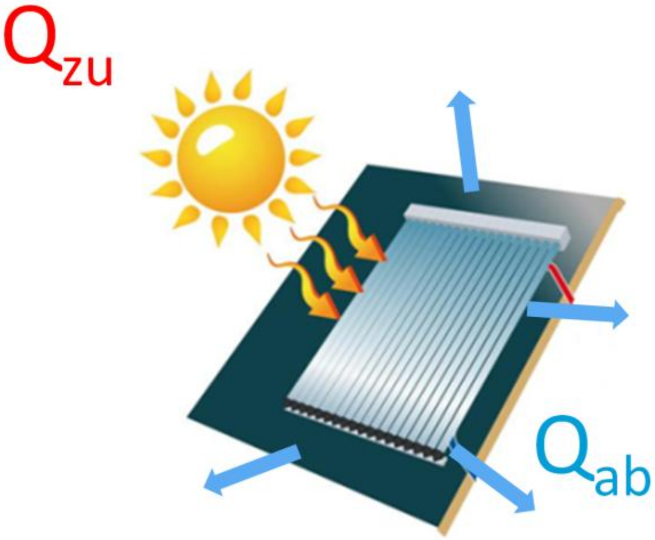

Figure 1: Principle heat balance of a solar collector

A second heat flow is generated by the difference between the actual (modeled) collector temperature and the ambient temperature. Since this temperature difference usually has a negative sign, it primarily leads to a reduction of the modeled temperature and is therefore called heat dissipation Q_{ab} in the following. Its amount is also determined by means of a polynomial formula but with its own fixed and variable coefficients.

Both heat flows are converted into temperature changes and added to the current temperature. All temperature values have a resolution of 0.1K.

These calculations are performed at one-minute intervals, providing the controller with 60 current model values per hour.

The fixed coefficients summarize all physical and design properties of the solar system. These include, for example, the collector area, the collector type, the heat capacity of the carrier medium, pipe lengths and the heat transfer of the pipe insulation. These coefficients are determined for commissioning and stored in the control system.

The variable components are used to detect uncertainties in the determination of the fixed coefficients as well as exemplary special features - such as contamination - of the respective solar system and are determined automatically by the control system.

When the so-called adaptation process is completed, the deviation between the modeled and the measured temperature is less than 0.5K.

This enables the model to provide a correctly modeled temperature for each collector or solar system.

If the solar pump is active, the heat input is determined and transferred to the control of the solar pump (see 4.2.1 Overheating).

2.6. Effect of the model

On the one hand, the model serves for the exact activation of frost protection measures. In order to be able to take these efficiently, a second - secondary - pump was installed in parallel to the solar pump and collector. This can be relatively small in size, since a closed circulation circuit is formed with minimal pumping losses. The direction of flow is opposite to that of the solar pump, since the direction of the free convection to be supported is also reversed when cooling is caused by frosty outdoor temperatures.

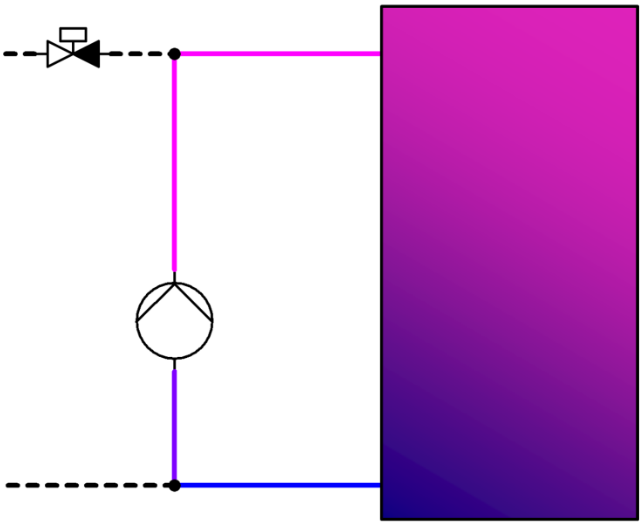

Figure 2: Secondary pump with collector

If the modeled collector temperature falls below a stored frost protection temperature - for example 4°C - the secondary pump is activated. The cold water in the lower part of the collector is transported into the building. At the same time, warmer water flows from the building into the collector. The secondary pump is switched off when the outlet temperature no longer rises. Now a stationary phase follows again. This is terminated when the modeled collector temperature again falls below the above-mentioned threshold and the secondary pump is activated.

This process is repeated until the increasing solar radiation leads to a sufficiently high modeled temperature or until switching off the secondary pump would lead to a significant drop below the frost protection temperature. In this way, frost protection is guaranteed up to an outside temperature of approx. -5°C in the system presented.

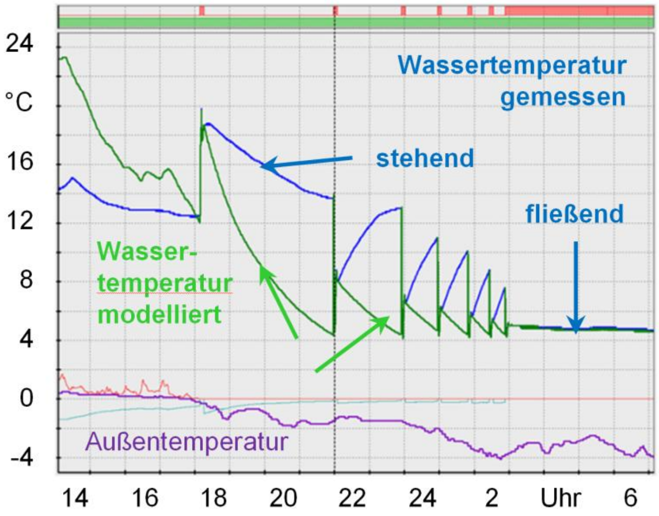

Figure 3: Frost protection with Stahrsolar temperature model

Further frost protection measures are described in point 4.
Only when the heat input is greater than the heat output, the (modeled) collector temperature increases.
When the modeled temperature reaches the set point, solar earning begins.

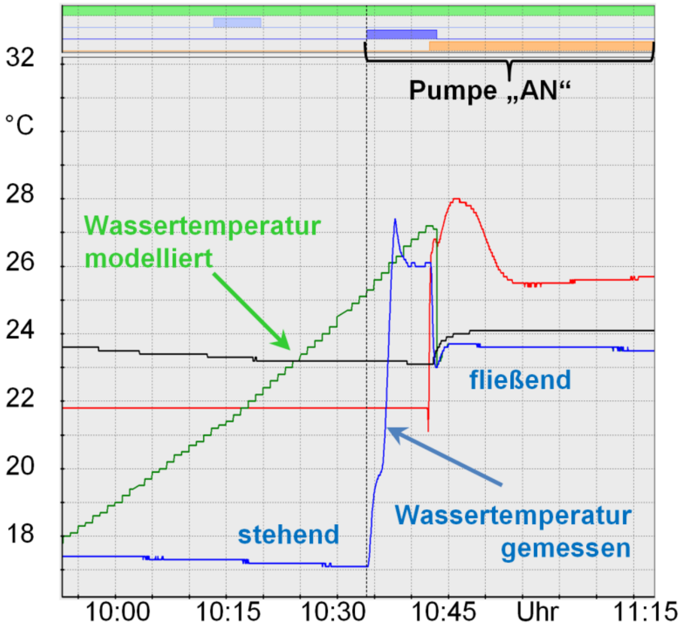

Figure 4: Solar start with Stahrsolar temperature model

Especially on cold winter days, the equilibrium between the two heat fluxes is only overcome when the solar radiation is relatively high. In most cases, however, the solar radiation is sufficient for frost-free conditions during daylight. Solar earning requires longer sunny periods during heavy frost. This results from the high heat dissipation due to the very low outdoor temperature and the heating-related high target temperature.

2.7. Protection against power failure

The functions of the model and the secondary pump must be guaranteed even if the mains voltage fails. Therefore, these have been protected by an independent power supply (UPS). The capacity was designed for a maximum power of 10W over a failure time of 10h.
Occurring mains failures thus had no limiting effect on the modeled collector temperature as well as the operation of the secondary pump.

2.8. Efficiency

To integrate the modeling of the collector temperature into existing systems, only a change of the software and a sensor for the solar radiation is required. The operation of the system remains unaffected during the installation.
The benefits are immediate, depending on the system to be optimized and the prevailing radiation conditions. The investment can be amortized within one year.

2.9. Summary and outlook

The temperature model has been successfully in use since 2017.

In a range of outdoor temperature from -30 to +38°C, the deviation between modeled and measured collector temperature remained below 0.5K.
Thus, the functional proof for the model approach as well as for the self-optimization was provided and tested over several years.
A safe and efficient frost protection for the collector filled with water was thus always given.

In 2021, the solar startup optimization model was incorporated into the control of a conventional solar plant with flat-plate collectors and glycol mixture.
The operator has noticed a significant difference: the plant now yields even on days with diffuse or low radiation. He is thrilled.

The robustness of the model approach and the reproducibility of the high model quality due to self-optimization make it possible to take further steps. Thus, similar to the automobile, it will be possible to generate a series of diagnoses for the solar system. On the basis of these, the operator will always be informed about the current status or be alerted to necessary maintenance or repair work on his system(s).

3. The variable reflector

3.1. Motivation

Especially in urban areas there is a very disadvantageous, almost unsolvable contradiction for renewable energies: the energy demand is very high - but the area available for new installations is very small. The prices for available land often make it uneconomical to use it purely for energy production.

One way to use existing built-up areas very effectively is to mount the collector on the facade and to place a reflector underneath this collector.

In the pilot installation described here, even a rigid reflective surface increased the solar yield by about 15%. Unfortunately, this installation was neither wind load resistant nor weather resistant.

The goal of the Stahrsolar reflector was a:

- cost-effective variant with
- high year-round availability
- self-protection
- self-cleaning and
- significant increase in yield due to optimal positioning of the reflection surface according to the current position of the sun.

3.2. The technology

The awning technology was chosen as the basis for the development and production of the prototype because it has the following advantageous properties:

- Proven product with many years of market maturity
- Motorized retraction as a proven protective measure against wind load and weathering
- Low space requirement for installation
- Operation usually possible without additional land use costs
- Secondary benefit (shading) is possible with clever placement
- Awning fabric and supporting structure offer sufficient flexibility to shape and position the surface according to the position of the sun.
- Mass of the overall construction requires relatively low load-bearing and adjustment forces. This allows for a compact and cost-effective drive for shaping and positioning the stretched surface

The top surface of the fabric was coated with 0.05mm aluminum. This increased the reflectance of the awning cloth to >91%.

The shaping and positioning of the stretched fabric surface is carried out by two independently controllable drive consoles. These are each connected to the awning at the level of the two folding arms.

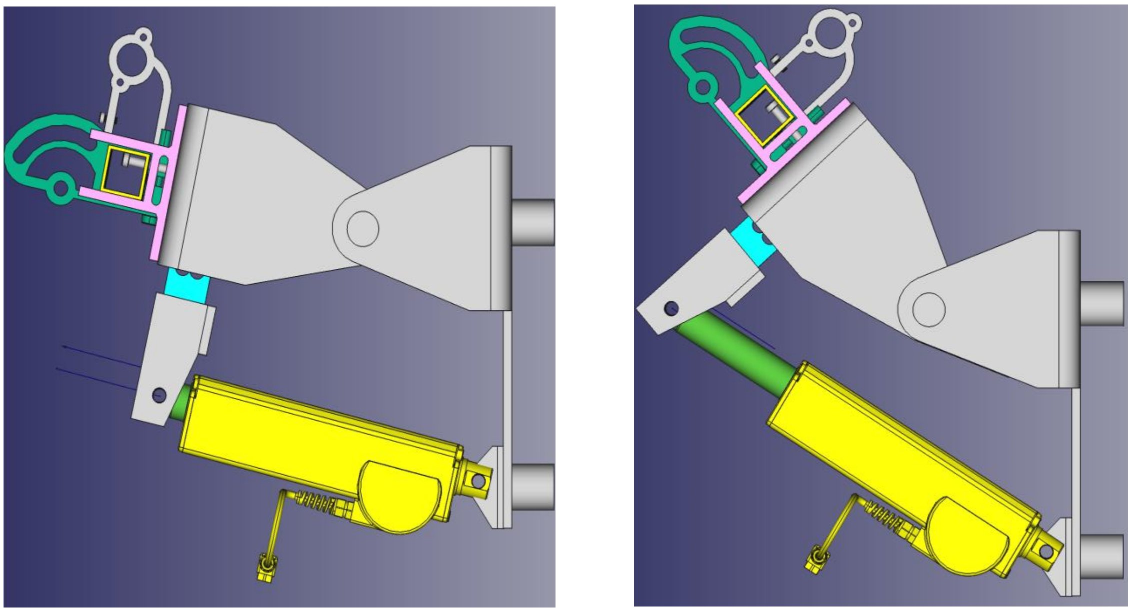

Figure 5: Drive consoles in minimum and maximum adjustment

To compensate for the azimuth of the sun, both drives are controlled equally. This changes the inclination. The reflector surface is tilted according to the direction of the sun. Therefore the support arm facing the sun is lowered.

Figure 6: Stahrsolar - collector with positioned reflector

3.3. Operation and maintenance

The awning technology is almost unchanged and therefore maintenance-free in line with all market products.
The components of the drive consoles were also designed to be maintenance-free.
To protect the construction from damage due to excessive wind load, the reflector is lowered in gusts above 3m/s and the tensioning bar is placed on the ground. The reflector is only retracted in the event of excessive gustiness or high wind force.
To protect against weathering, the reflector is retracted during rain (danger) and at sunset.

During retraction, the winding of the fabric leads to minimal relative movements between the individual layers of fabric. The smooth and coated surface of the fabric rubs against the rough underside of the layer above. This leads to abrasion of dirt particles. The reflector surface is thus self-cleaning and maintenance-free.

As soon as the sun has reached an azimuth stored in the control system the next morning, the solar radiation is sufficient and the wind speed is below a safety value, the reflector is extended and positioned.

3.4. Results

When the sun is behind the collectors plane, the reflector allows solar radiation to be re-reflected onto the shaded collector. This allowed starting the solar up to 2hours earlier.

At maximum solar elevation, the collector's output could be increased by about 30%. This was primarily due to the compensation of the shading of the collector by the roof overhang.

The installation of the reflector close to the ground resulted in a limited tilt angle. As a result, only a partial potential could be used when the sun was close to the perpendicular to the collector plane.

On an annual average, an increase in solar yield of 50% was achieved.

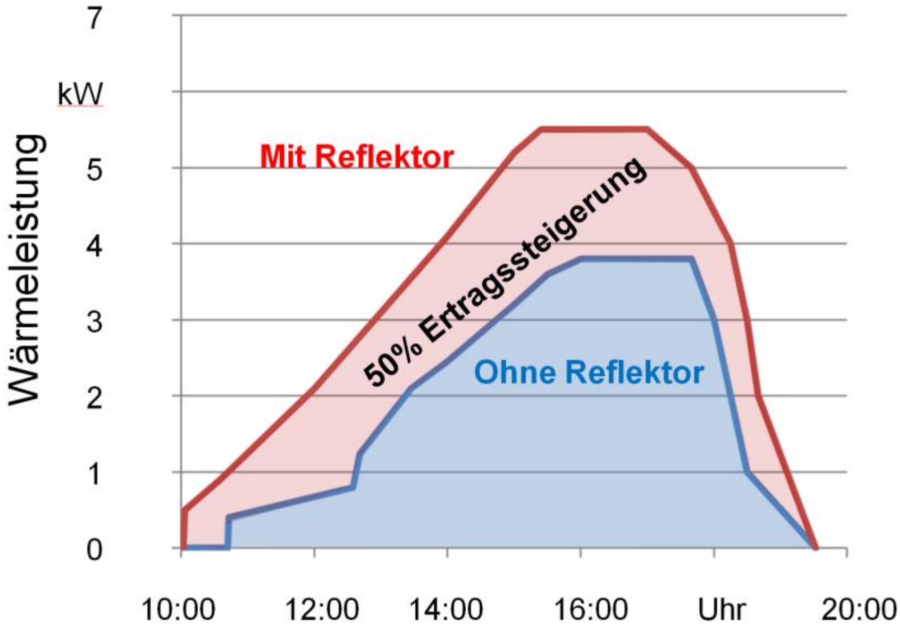

Figure 7: Yield comparison with/without reflector

3.5. Economic efficiency

A concrete prognosis of achievable yields is currently not possible. The greatest uncertainties currently lie in the industrial coating of the cloth and the industrialization of console production.

From today's point of view, a reflector price of approx. 300€/m² should be achievable for the customer.

An application has been submitted to the German Federal Office of Economics and Export Control (BAFA) for inclusion in the list of eligible technologies. A positive decision would further increase the attractiveness of the technology.

3.6. Summary and outlook

The variable collector has been successfully in operation since 2019 without failure.

It has significantly increased solar yield.

2nd generation drive consoles are planned for 2021/22. The new kinematics will allow further optimization of reflector positioning and thus a further increase in solar yield.

It can be assumed that the use of a reflector will reduce the minimum economically viable collector area.
Especially for urban areas, the attractiveness of smaller solar collectors should be increased.

4. The optimal variable hydraulics

4.1. Motivation

At Stahrsolar, an important principle for the design of the hydraulic connection of the collector to the storage tank or the heating system was that the system should be operated with minimum pumping losses and efficient superheating.

Efficient superheating is the optimum difference between the temperatures at the collector inlet and outlet, which is a compromise between the opposing thermal and hydraulic losses.
The lower the flow rate / the electrical pumping power / the demand for auxiliary energy, the greater the temperature rise. The greater the temperature rise, the more heat is dissipated by the collector and all the system components outside (of the building to be managed) back into the environment and can therefore not be used. The reduction of this thermal loss can only be achieved with an increased volume flow / increased electrical pumping power.

In order to find the respective optima, the interactions of the factors at constant heat dissipation (e.g. by outside temperature and useful heat sinks) were determined and graphically filed. Thus important known effects and their effective ranges became representable.

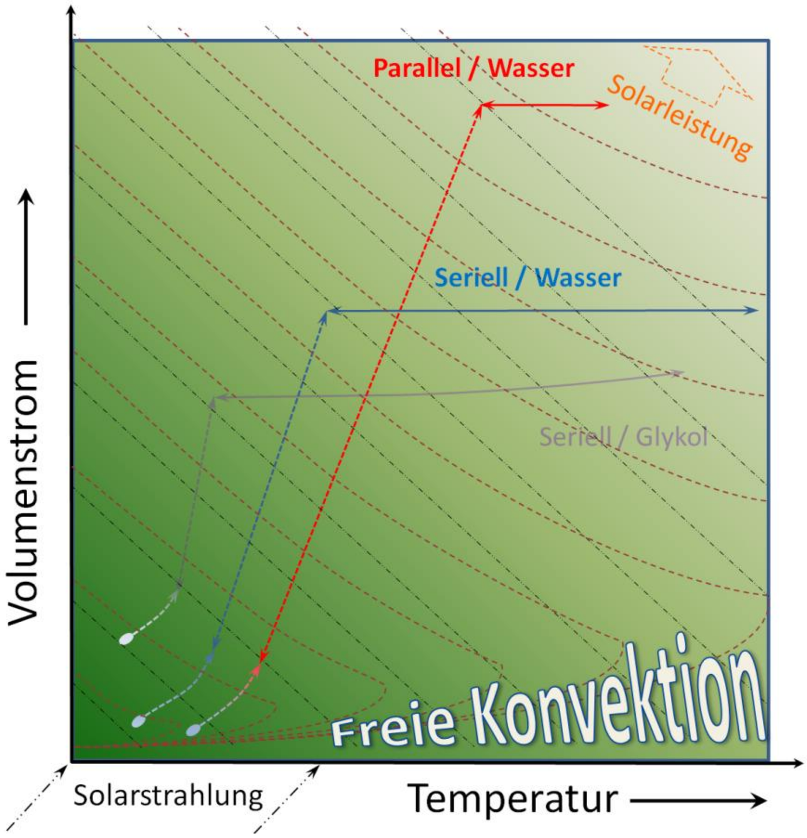

Fig. 8: T- $\dot{v}$- PS diagram

a) The lower the volume flow at constant radiation, the higher the outlet temperature.
b) Outlet temperature and thermal losses are changing in the same direction
c) With decreasing heat capacity the outlet temperature increases
d) With decreasing viscosity the volume flow increases at constant pumping work (see ‘Seriell/Glykol’).

A reflector increases the maximum solar output of a collector of the same size by about 40%. This should be used with as little additional thermal or electrical losses as possible.

Frost protection should be achieved with minimal thermal and electrical effort.

4.2. Implementation

4.2.1. Superheating

In order to keep the superheat constant, the volume flow must be adapted to the solar radiation or the heat input. This task is performed by a conventional solar pump with variable flow rate and an associated control unit.

In order to precisely maintain the set superheat, the control command for the solar pump is determined on the basis of the pump's delivery characteristic and the heat input. This is provided by the Stahrsolar collector temperature model. Remaining deviations between the set point and the actual superheat were almost completely compensated by a PI controller. Thus the thermal losses are optimal.

4.2.2. Pressure losses

An important feature of the solar system for minimizing pressure losses was the parallel flow through two sub-collectors of the same size. This leads to following positive effects compared to a serial flow:

- Doubling of the minimum pipe cross-section
- Halving of the pipe length with minimum cross-section

When the reflector is extended and the angle of difference between the direction of the sun and the perpendicular to the collector plane is large, the sub-collector facing away from the sun receives significantly more radiation and is thus heated more. In order to keep the overheating of both sub-collectors equal, the volume flow of the cool collector is throttled accordingly by means of a distribution valve. To reduce the rising temperatures, the flow rate of the solar pump is increased.

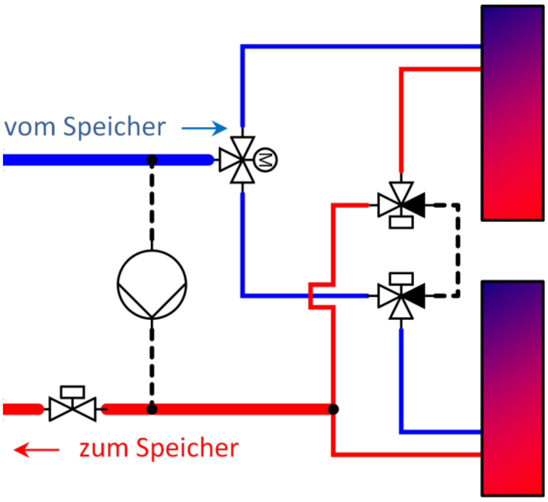

Figure 9: Solar operation with parallel flow through the sub-collectors.

Furthermore, it should be possible to achieve maximum superheating by flowing through the entire collector in series.

- ⇨ Very advantageous in case of low solar radiation (solar start, cloud cover, sunset, etc.).
- ⇨ Helpful for hot water production
- ⇨ Can be used in case of high storage loading for deterioration of efficiency => stagnation protection.

In this mode the flow rate is used, which was determined as the best compromise of heat transport, superheating and information content of the measured temperature value. It was 52% of the flow rate of the solar pump.

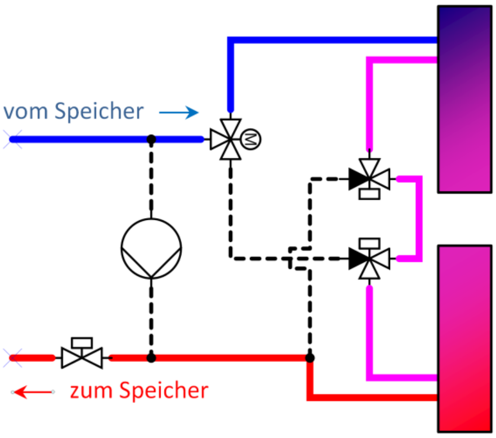

Fig. 10: Solar operation with serial flow through the partial collectors.

The hydraulic circuit shown, in combination with appropriate control algorithms, allows switching between the advantages of the two operating modes as needed.

4.2.3. Extended frost protection

All frost protection measures are carried out with parallel flow. This means that a minimum is required both in terms of frost protection heat and in terms of electrical pumping power.
In case of stronger frost, additional frost protection heat is required in the secondary collector circuit - consisting of the collector and the secondary pump. This is supplied from the storage tank via a 3-way mixing valve. This ensures the control of a constant low collector temperature - e.g. 3°C.

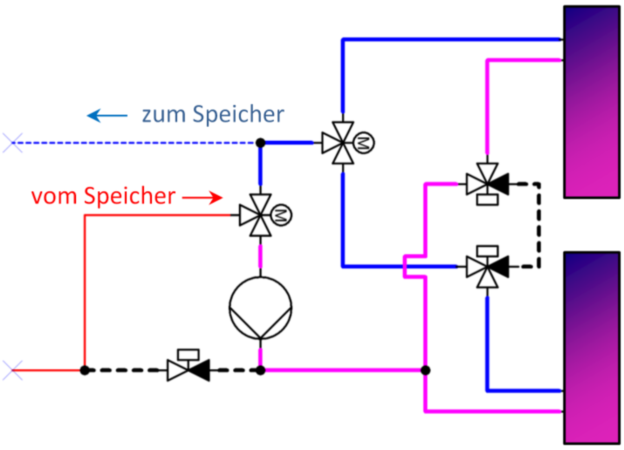

Figure 11: Secondary collector circuit with temperature control valve

4.2.4. Cooling purge

The direct connection of the collector to the heating circuit enables the use of the residual heat of the water in the collector and the pipes when the sun is not shining anymore.
For this purpose, the heating circuit pump is activated if necessary and the current set temperature of the heating flow is increased. Now the collector is purged with the colder water of the heating system. When the temperatures are balanced, cold purging is terminated.

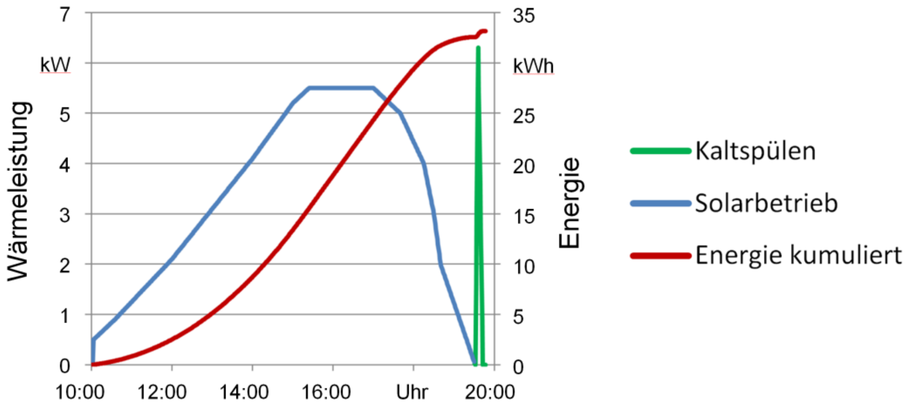

Fig. 12: Utilization of residual collector heat by cooling purge

In this way, additional collector heat, that could no longer be absorbed by the storage tank and would have been released unused into the environment, is used.

Due to the small amounts of heat involved, there is no so called ‘activation of building components’ in the original sense.

4.3. Economic efficiency

Compared to a conventional system, the costs of installation are considerable and only make economic sense for new installations.

The valves used as well as the carrier medium water are maintenance-free. This leads to a considerable advantage in operating costs compared to systems with antifreeze.

Due to the lack of comparative systems, it has not yet been possible to produce an exact profitability forecast. However, it can be assumed that using water as a carrier medium and the Stahrsolar temperature model a significant energy advantage can be achieved compared to current systems. Thus, the installation of a Stahrsolar hydraulic system should pay for itself more quickly for systems filled with water.

4.4. Summary and outlook

The requirements for the hydraulics were met.

- Solar start or solar earning was possible even with low solar radiation.
- Up to a specific collector power of 700W/m², the volume flow could be controlled and thus the optimal superheating could be guaranteed. Higher outputs were rarely achieved, which is why the resulting thermal losses can be classified as negligible.
- In solar operation, the demand for auxiliary energy was on average less than one percent of the solar output.
- Only one functional extension was required to use the residual heat of the collector.
- A very effective and efficient frost protection could be presented.
- The system has been in operation since 2017 and functions faultlessly

The advantage of equalizing the overheating of the partial collectors in parallel operation is currently classified as economically negligible. This statement is to be verified with reflectors of newer generations.

The present findings motivate to further investigate the potential of this variability. For this purpose, for example, the available data can be used to validate numerical analysis.

Regardless of the carrier medium, variable perfuse the collector can contribute to significantly more efficient system operation.

5. Summary

With the temperature model, the variable reflector as well as the variable hydraulics of Stahrsolar, possibilities were shown to increase the solar yield and at the same time to reduce the need for auxiliary energy.

The use of water as a carrier medium and a reflector are approaches that will increase the attractiveness of solar thermal energy, especially under urban conditions.

With the façade installation, an aesthetic solution was implemented that has a primarily decorative effect and allows the character of a collector to recede into the background.