

The Key For Optimizing Large-Scale Solar-Thermal Systems is Combining Parabolic Mirrors, Evacuated Tube Collectors and H₂O

Rolf Meissner and Stefan Abrecht

1. Abstracts

After nearly 20 years of research and development, as well as the practical experience gained through the installation of more than 30,000 systems using the AquaSystem® principle (pure water as the heat transfer fluid), it is evident that utilizing Concentrating Parabolic Compound (CPC) Mirrors with Evacuated Tube Collectors (ETC) in the construction of large scale solar thermal systems produces superior results. High temperature collectors increase the efficiency factor, allow an all-season application and are the key for effective heat storage.

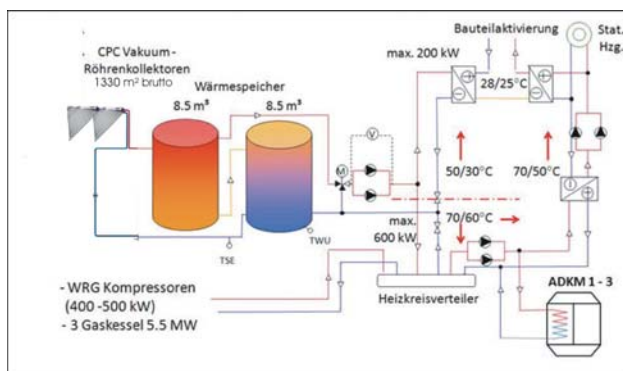
2. Some actual examples

Paradigma, a German high-tech company specializing in solar thermal systems, engineers large scale solar systems designed to be integrated into conventional hydronic heating and domestic hot water systems. Since 2006 more than 50 installations have been commissioned, including the project for FESTO. The FESTO system is the largest solar cooling system in the world, installed with 1,330 m² (14,363 sq. ft.) of Paradigm's CPC-ETC collectors. This solar field delivers heat to an adsorption chiller, cooling 27,000 m² (291,600 sq. ft.) of office space in summer. Since the existing hydronic network is so large, the interface was accomplished without a heat exchanger, requiring only a simple buffer storage tank of 17 m³ volume (4,490 gallons) (fig. 1, 2, 3).



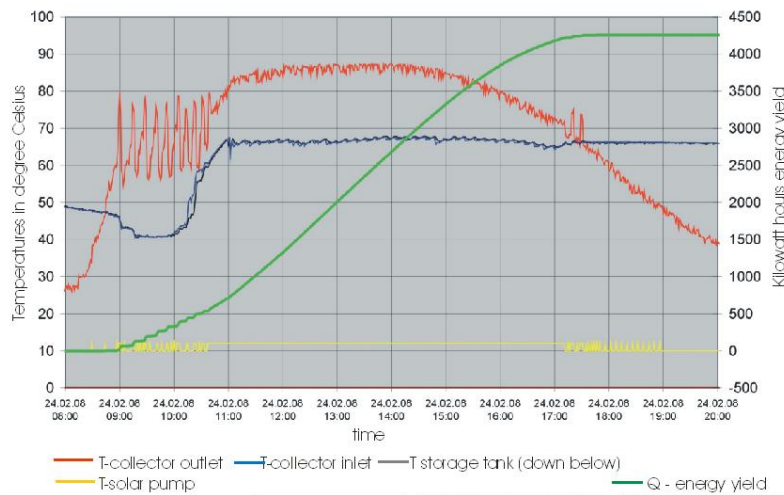
fig. 1, 2 Esslingen, Germany: FESTO AG, 1,330 m² gross collector area for cooling and heating

The collector field does not contain any de-aerators, valves or other devices in the outdoor area. While the final design is quite simple, the calculations for self-filling and self-de-aerating require complex mathematical thermal hydraulic calculations.



solar application	cooling at 75-95 °C (167 – 203 °F)
	heating at 50-70 °C (122 – 158 °F)
collector gross area	1,330 m ² (14,363 sq ft)
volume flow	30 m ³ /h (7,925 gal hr)
storage tank	17 m ³ (4,490 gal)
peak power	1.2 MW (4.1 Mio BTU/hour)
max. continual power	0.65 MW (2.2 Mio BTU/h)
guaranteed yield	500 MWh (1.71 Billion BTU) p. annum
electrical energy req.	2.5 MWh (8.53 Million BTU) p. annum

fig. 3 FESTO, hydraulic scheme, source (HfT-Stuttgart, FESTO AG)



This system was delivered with a performance guarantee from Paradigma and the energy delivered to-date exceeds forecast. On sunny winter days nearly 4.3 MWh of power are delivered to the tank at temperatures greater than 80 °C (176 °F) (fig. 4). The collector output during this time is 3.2 kWh per square meter gross collector area – an outstanding result for a day in February.

fig. 4 FESTO AG, temperatures and energy yield on February 24th 2008

In other installations an additional storage tank was expendable because the hydraulic system was able to absorb the solar energy as it was generated. This is often the case in industrial systems since the volume of water in the existing hydronic system is large enough to readily absorb the solar input. As a prototype a solar thermal system for a large sauna bath was installed like an additional boiler (fig 5, 6). The solar heat is directly fed into the existing heating network (fig. 7).



fig. 5, 6 Graftschaff, sauna bath, 98 m² collector area, support of a heating network

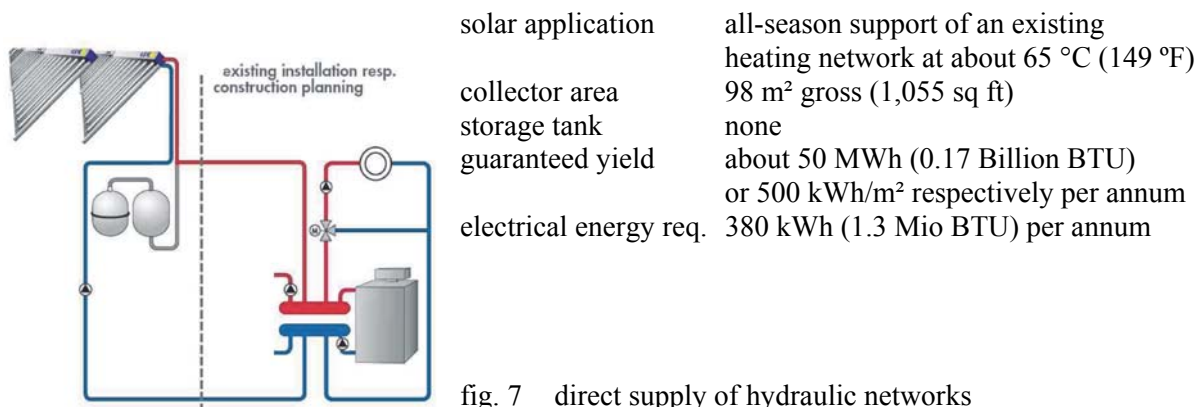


fig. 7 direct supply of hydraulic networks

The sauna bath installation proves that a direct feed hydraulic principle can be applied to district heating networks. In the near future we believe connecting solar fields to district heating systems will be common practice, resulting in benefits to communities, the environment and the solar industry.

Many standard large scale solar systems are running without complication. Predictable performance, no downtime and low maintenance are common characteristics. The key design feature that allows trouble free operations is water – using water as the solar collector heat transfer fluid removes most of the complications for transferring heat downstream of the collector field. Commercial buildings,

condominiums, hospitals, schools and gyms, hotels, restaurants, and industrial operations are all benefiting from the Aqua Principle (fig. 8).



fig. 8
large-scale solar-thermal
systems for domestic hot
water and space heating

3. History

At the end of the 1990's the prospects for expanding the application of cost effective solar thermal collectors was not promising. Flat plate collectors achieved high stagnation temperatures, but their efficiency at temperature of 60 to 150 °C (140 to 302 °F) was not promising. In addition, the problem of stagnating glycol-filled collectors is accentuated at higher temperatures. The primary design effort at this time was focused on preventing stagnation, which was critical. A standard solution was to use a huge storage tank, which partially solved the problem of stagnating collectors, but greatly reduced the cost effectiveness of the installation.

Paradigma has been involved in solar research and development since 1988, and launched an innovative flat plate design many years ago. In 1997 Paradigma forged a new path and turned to vacuum tube technology. Paradigma's superior design and focus on quality has been widely accepted, evidenced by its more than 50 % market-share of ETC in Europe. Paradigma is a vertically integrated manufacturer, having control over every production process, from molten glass to forming of high-precision CPC mirrors; cutting, forming and brazing of internal pipe works, assembly and final quality test.

The double wall vacuum tube system results in minimal heat losses and is key to applying Paradigma's patented frost protection technology. Paradigma is the first and only company that has overcome the problems associated with using water in year-round pressurized solar systems. With high-efficiency collectors and sophisticated feeding algorithm, the solar system can be protected from freezing in a cost effective way.

4. The heat transfer medium water

In 2003 Paradigma introduced the AquaSystem®, which uses water as the heat exchange medium. Because of the low heat losses of the CPC vacuum tube collectors, only a small amount of energy, about 2 to 4 % of the yearly solar energy gain, is required for frost protection. In most cases this is stored solar energy that is not needed for domestic hot water requirements. Achieving frost protection by returning a small amount of unutilized solar hot water was a major advancement to existing solar technology and resulted in the award of the German Federal Award Bundespreis 2006. The market has fully embraced the AquaSystem®, as more than 35,000 systems are now installed.

The advantages of the AquaSystem® over conventional solar collector systems are numerous. The operation with water

- allows easy, direct connection to the in-house heating network,
- requires less equipment such as heat exchangers, de-aerators, valves, pumps and controllers,
- is the precondition for the use of efficient, small, single coil storage tanks,

- eliminates the high costs for antifreeze and the associated running costs,
- considerably reduces the cost and time for installation, commissioning and repairs,
- ensures a long operating life with almost constant performance,
- removes all risks associated with thermal stagnation and
- minimizes maintenance costs and downtime.

Using state-of-art CPC vacuum tube collectors ensures a maximum harvest of solar energy and a system that has a long operating life and is virtually maintenance free.

Unfortunately, full recognition of the significant benefits of water compared to glycol has yet to be fully incorporated in the technical standards. Chapter 7 of DIN EN 12975 is related to power performance and was published without consideration between the physical differences of these two fluids. At an operating temperature of 40 °C (104 °F) glycol has only 88 % of the heat capacity, 62 % of the heat conductivity, 75 % of the heat-transfer coefficient, up to 3.85 times higher pressure losses and 3.8 times the viscosity of water. In addition, a water-glycol heat exchange requires up to 3 times the heat exchanger area than a water-water heat exchange to get the same number of transfer units. And the higher the temperatures are, the wider the performance differences.

These large differences are also ignored in solar simulations programs, ratings issued by independent testing agencies, dollar-based tax rebate programs, technical training programs and marketing literature of those companies whose products are tested and rated with water, but installed using glycol.

5. Function control and system monitoring

Germany has the largest solar market in Europe. It also is well known for the high level of training and skill of its craftsmen. But a recent market study concluded that as many as twenty-five percent of solar systems installed in Germany were not working as designed. It is easy to understand how this could occur if it is known that almost all these systems were conventional glycol system with boiler back-up heat. If the system doesn't freeze and there is hot water at the faucet, there is no suspicion of a problem. However, installations without antifreeze must be error-free. The Paradigma AquaSystem® is equipped with a solar controller that has sophisticated and reliable diagnosis software which constantly monitors the system. If the system does not perform the way it was designed, an acoustic alarm will call attention to the deficiency.

6. The storage of solar thermal heat

Having a clear understanding of the temperature stratifications in storage tanks is critical in optimizing the design of the solar system. This knowledge will impact the number of collectors, the size of the tank, the temperature coming from the collector, and piping arrangements. Our principal concept is to avoid large storage tanks for domestic hot water applications. Using set-point control logic, high temperature water is delivered into the top of the tank in small bursts or buckets. Supplying hot water from the collector in this fashion results in higher stratification layers in the tank. Domestic water is drawn from the top of the tank, and after mixing, the quantity of hot water at the facet can exceed that provided by tanks twice the size.

Stagnation is a normal operating condition in water systems. If the domestic water tank and / or the heating buffer tank are heat saturated, the collector water will steam off without incident, condensing into the domestic water coil or expansion tank. During the stagnation period, the system cannot be activated until the collector cools and water is pushed back into the collector from the expansion tank. In most cases stagnation will occur late in the day and since the storage tanks are at heat capacity, the homeowner experiences no loss of solar performance.

In the near future, restarting Paradigma Aqua Systems® from thermal standstill will be standard. This will allow the utilization of the storage capacity of collector field, which holds 0.5 kWh per m² collector area and represents about 1/100 of the annual energy harvest in a residential system. A solar collector system that can be restarted from standstill at any time promises a much higher annual energy harvest and will allow for a reduction in collector field sizes and water storage tank sizes.

7. The power performance of several solar-thermal collectors

The thermal efficiency factor is also known as the collector efficiency factor, represented as $\eta(x)$. It is the percentage of the energy provided by the sun that the collector can convert to heat water. It can be easily calculated at any operating point from the three performance variables issued after the Solar Keymark Tests. Those performance variables are: conversion factor η_0 , loss coefficient factor a_1 , and loss coefficient factor a_2 . Since the efficiency of a collector moves in a non-linear way to changes in insolation level (G_s in watts / m²), ambient temperature (T_u) and average ($(T_{inlet} + T_{outlet}) / 2$) manifold water temperature (T_k), these variables must also be known. So the formula to calculate the thermal efficiency of a solar collector is:

$$\eta(x) = \eta_0 - (a_1 * x) - (a_2 * G_s * x^2) \text{ where } x = (T_k - T_u) / G_s$$

The characteristic curves in the following diagram are based on gross collector area, since installations are planned, paid for and subsidized on this basis.

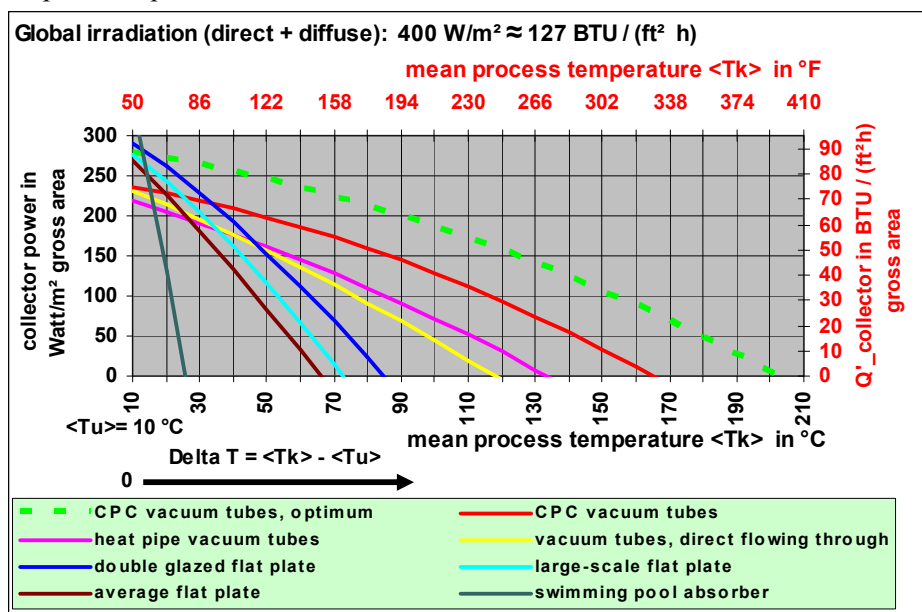


fig. 9 Heat power performance of collectors at an irradiation of 400 W/m²

The graph in figure 9 assumes an ambient temperature T_u of 10 °C (50 °F) and irradiation G_s of 400 W/m². The other factors that determine the slope of the graph are based on the three performance variables from the SolarKey Mark test. The x-axis is the average water temperature (it approximately corresponds with the process temperature) based on an ambient temperature of 10 °C (50 °F). The diagram demonstrates that when flow rate temperatures are between 35 to 50 °C (95 to 122 °F) all flat plate collectors drop under 150 W/m² (48 BTU/ft²h), while existing CPC vacuum tube collectors deliver this power at 90 °C (194 °F). The green broken line represents a „theoretical“ CPC vacuum tube collector that could be manufactured based on state of the art methods.

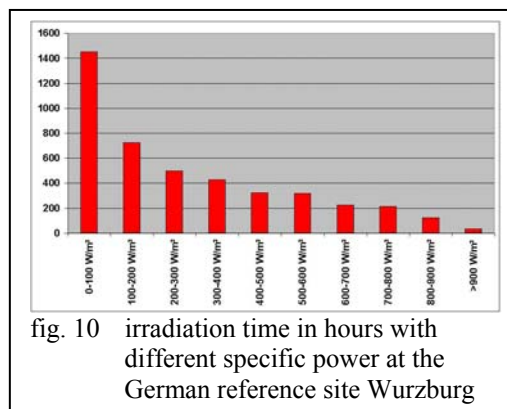


fig. 10 irradiation time in hours with different specific power at the German reference site Würzburg

If there is no temperature difference ΔT , every collector achieves its individual maximal efficiency factor η_0 . The hotter the collector, the higher the ΔT , but the efficiency factor decreases. The higher the heat loss, the sooner the efficiency factor reaches zero with rising collector temperatures. However, the efficiency factor decreases faster with weaker irradiation G_s levels. Thus collector sellers try to present their efficiency factor using

irradiation levels of 800 W/m² to 1000 W/m². These are unrealistic anywhere on the globe. Würzburg, Germany gets only 11 % of the irradiation with 800 W/m² or more, and 13 % with less than 200 W/m²

(fig. 10). The yearly average of 397 W/m² ignores the range below 100 W/m² because it is completely irrelevant for flat plate collectors and brings only about 5 % of the yearly energy harvest for tube collectors. Otherwise the average would be even lower.

Applying solar thermal energy to drive solar power electric generators is promising technology. However, transforming thermal energy into mechanical energy changes the efficiency calculation. The thermal efficiency factor measures how much heat is transferred from solar energy but says nothing about the part that could be used in a heat engine. The second law of thermodynamics and the Carnot principle puts a fundamental limit on the thermal efficiency of heat engines.

The Carnot factor for a collector is:

$$\eta_c = \frac{\langle T_k \rangle - \langle T_u \rangle}{\langle T_k \rangle + 273K} = \frac{\langle T_k \rangle - 10K}{\langle T_k \rangle + 273K}$$

$\langle T_k \rangle$ mean collector or process temperature

$\langle T_u \rangle$ mean ambient outdoor temperature with $\langle T_u \rangle = 10 \text{ }^\circ\text{C}$ (50 °F)

273 K (= 491 °F) distance between Celsius scale and absolute zero in degree Kelvin

400 W/m² (127 BTU/ft²h) irradiation level

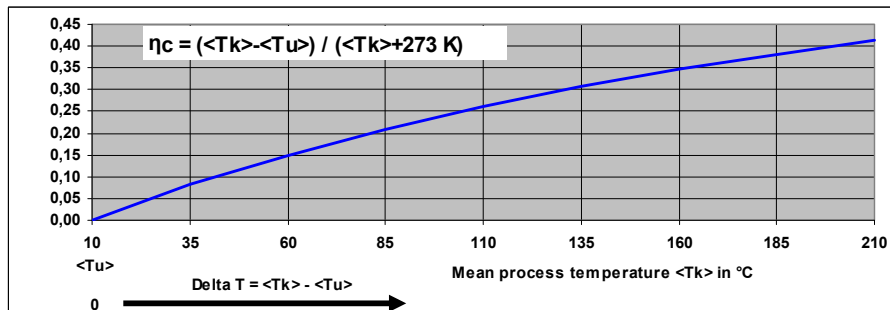


fig. 11
The Carnot factor η_c

η_c is the percentage of heat that could be transferred into power or electricity. It is about 40 % with 200 °C process temperature. So even after de-rating a solar thermal system for the affect of the Carnot principle, the system efficiency matches that of current photovoltaic systems. It is easy to imagine a thermal solar system providing the energy to heat water and provide electricity.

The thermal collector efficiency factor multiplied by the Carnot factor and the mean global irradiation G_s results in the *thermodynamic collector performance* P_L value depending on the process temperature $\langle T_k \rangle$. The performance value weights the achievable heat performance of a collector concerning the universal thermodynamic usability.

$$P_L = G_s \eta_0 \eta_c \text{ with } G_s = 400 \text{ W/m}^2 \text{ (127 BTU/ft}^2\text{h).}$$

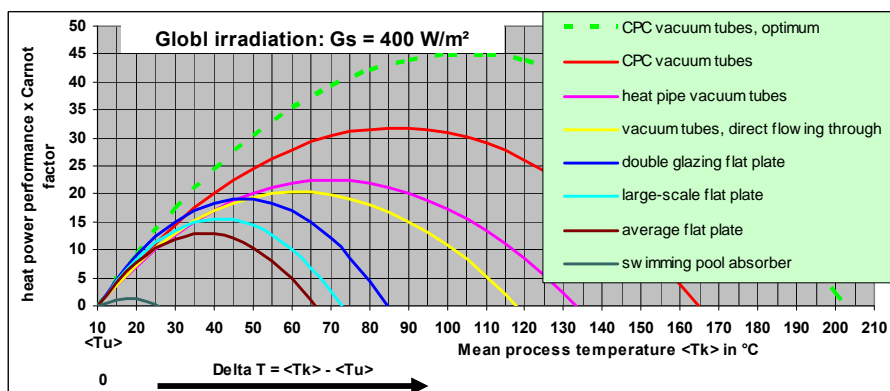


fig. 12
thermodynamic efficiency or collector performance P_L at an irradiation of 400 W/m² (127 BTU/ft²h)

All performance value characteristics start at zero. Heat at the level of the mean ambient temperature is useless. Collectors with high η_0 have the steepest slope. Collectors with the best thermal characteristics have the longest slope. Sometime the decrease of the collector efficiency factor will outweigh the increase of the thermodynamic efficiency factor with every collector. At the

characteristic collector temperature T_C you get a maximum performance. Then the performance value decreases and reaches zero exactly together with the thermal efficiency factor because the thermal gain decreases with increasingly higher temperatures.

A collector reaches its performance maximum at the characteristic collector temperature T_C and a different T_C results at different irradiation levels. Every collector can be used at lower temperatures than its T_C , but it makes no sense to use collectors in applications that need higher temperatures than their specific T_C . For example, in a domestic hot water application that must exceed $65\text{ }^\circ\text{C}$ ($149\text{ }^\circ\text{F}$) to meet the anti-Legionella bacteria standard, a flat plate collector would not be appropriate.

The characteristic collector temperature depends on the location. The black line at 400 W/m^2 represents Würzburg, Germany, this is representative of the main population centres of Europe and the North America. Mean irradiation up to 600 W/m^2 is possible in the Mediterranean area, up to 650 W/m^2 in California, up to 700 W/m^2 in Australia and India and even up to 750 W/m^2 in the Middle East.

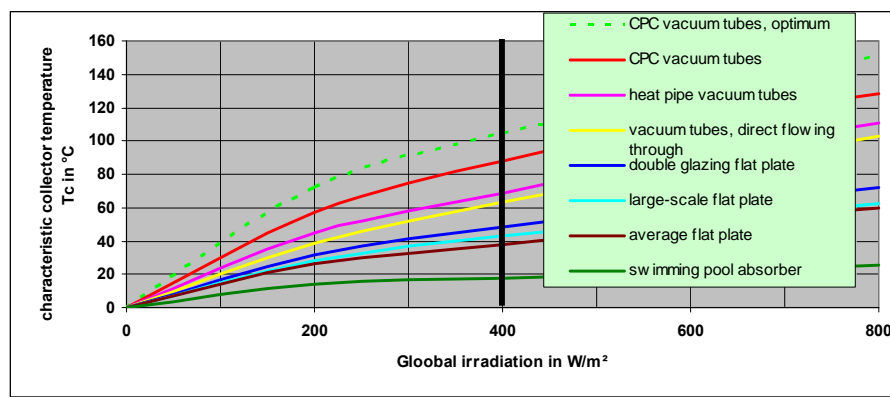


fig. 13 characteristic temperatures as a function of irradiation for collectors

8. The collector gain and the cardinal point

The optimal orientation of a collector - south, tilted according to the latitude - is often not possible. Roof slope, building orientation and obstructions will many times prevent optimal orientation. CPC vacuum tube collectors can compensate for an unfavourable orientation with the smallest additional collector area. In an extreme case with east orientation, flat plate collectors need 90 % more area while CPC vacuum tube collectors need 40 % more. In addition, CPC collectors have higher efficiency factors at lower irradiation levels, which is common on unfavourable roof orientations.

9. Concerning the advantages of higher temperatures

9.1. General remarks

In general, solar energy can be more effectively applied the higher the water temperature. Higher temperatures allow for a wider range of applications and expand the heat storage capacity of tanks. Solar cooling and thermal power generators only work with high temperatures. It is easy and cost effective to reduce water temperatures with mixing valves. On a cost per delivered kilowatt basis, CPC ETC collectors are competitive with low temperature collectors. The labour cost component per installed collector is similar for all types of collectors, but the labour cost per installed kilowatt is lower for high temperature collectors.

9.2. High collector temperatures increase the efficiency factor of the installation:

If the solar system is considered the primary source of heat, conventional backup heating is avoided only if the solar outlet temperature remains above the boiler low limit point. Boiler efficiency factors are at their lowest point outside of the heating season, so every boiler cycle avoided by solar heat results in savings exponentially higher than heating season boiler cycles.

If a 85% efficient oil boiler with an internal water volume of 60 l (16 gal) has to heat the system water from $20\text{ }^\circ\text{C}$ ($68\text{ }^\circ\text{F}$) to $70\text{ }^\circ\text{C}$ ($158\text{ }^\circ\text{F}$) before it can heat 150 l (40 gal) of hot water in the tank by $5\text{ }^\circ\text{C}$ ($41\text{ }^\circ\text{F}$), then only 16 % of the consumed fossil fuel is used for domestic water heating. Only when solar collector systems deliver water at temperatures which eliminate the need to start the boiler, will every solar kilowatt-hour save 6.25 kilowatt-hours of fossil energy.

On an annual basis, standby losses of hydronic heating systems can be as great as the annual solar energy harvest. The only way to allow backup heating systems to go dormant for extended time periods is to delivery high temperature solar water into domestic water storage or heating buffer tanks. Low temperature collectors or systems utilizing delta-T-controllers which prevent high temperatures, can never realize the benefits of backup heating systems going dormant for extended periods.

Permanently high collector temperatures result in large temperature differences, which decrease the volume flow demand. This has a direct effect on the amount of electrical pump energy and pump running time. Electric energy can be cut in half by using high temperature methods.

9.3. High collector temperatures increase the storage capacity:

If the temperature in the storage tank is equal to the temperature of water desired at the faucet, then the amount of usable hot water is equal to the water volume in the tank. The amount of usable hot water is greatly expanded by allowing the storage temperature to increase over the design use temperature. The tank volume is effectively “enlarged” by storing water higher than consumption temperatures.

Consider a heating circuit with a 60 °C (140 °F) supply and a 50 °C (122 °F) return and a solar buffer tank at 90 °C (194 °F). For every litre at 90 °C, 4 litres (1 gal) of water at 60 °C can be fed into the heating network. A low temperature collector needs 3 times the tank volume to yield the same heat energy at 70 °C (158 °F). If the heat from the buffer tank is used through a heat exchanger (glycol system), the usable energy will be even smaller.

Of course storing water at higher than consumption temperatures can result in much smaller tanks being able to deliver the same amount of hot water. It is possible for high temperature water tanks to be half the size and deliver the same amount of hot water at the faucet.

9.4. High collector temperatures allow an all-season application and provide confidence with which one can plan

Every planner and user is interested in an efficient all-season application of the solar collector system. The performance of low temperature collectors drops considerably with falling outside temperatures. In winter or when the weather is not optimal, CPC collectors continue to perform at high levels. The technology is here today to utilize a single solar field for multiple purposes: domestic hot water, space heating, space cooling, or electric generation. The possibility to combine applications and realize a full solar harvest over twelve months can only be accomplished when water is store at its highest thermodynamic value.

10. Summarization

- Double wall evacuated tube collectors with compound parabolic mirrors have the highest thermal efficiency and achieve excellent performance in a wide range of environmental conditions.
- Using water as a heat transfer medium has positive cost benefits, simplifies designs, and allows direct integration into existing heating or cooling systems.
- Having an understanding of thermodynamic principles and thermal efficiency formulas is necessary to calculate and compare the performance of different collector designs.
- There are numerous advantages to harvesting solar energy at the highest possible water temperature. Design flexibility, potential to do solar cooling, thermal electric generating, and use of smaller tanks are some benefits of using the hottest water possible.
- Being able to “hot start” stagnate solar fields allows the utilization of the storage capacity of collector fields. A solar collector system that can be restarted from standstill at any time promises a much higher annual energy harvest and will allow for a reduction in collector field sizes and water storage tank sizes.

The authors



Rolf Meissner, PhD, is a physicist and has worked for the German solar trendsetter company PARADIGMA since 1990, as a product manager and development engineer for controllers, storage tanks and concepts for large-scale solar collector systems. In 2006 he founded the department specializing in solar-thermal large-scale installations and process heat.



Stefan Abrecht, M. Sc. in mechanical engineering, developed all Paradigma flat plate and vacuum tube collectors during the last 20 years as well as the collectors from the Paradigma subsidy company RitterSolar. He was also founder and first CEO of the German-Chinese joint-venture Linuo Paradigma.

® Paradigma Energie- und Umwelttechnik GmbH & Co. KG