# Solar water systems – design and performance

**The amount of hot water a solar heater produces depends on the type and size of the system, the amount of sun available at the site, the seasonal hot water demand pattern and the installation of the system. Yet simply positioning the collectors so that they receive maximum annual radiation does not necessarily result in maximum system effectiveness. GRAHAM MORRISON provides a useful overview of system designs, then comments on their comparative performance.**

Solar water heaters are made up of a solar collector array, an energy transfer system and a thermal storage system; while active solar water heaters use a pump to circulate the heat-transfer fluid through the collector, passive – or thermosyphon – systems use thermally driven natural circulation of the working fluid.

Solar water heaters are also classified as open loop ('direct') or closed loop ('indirect'). Open loop systems circulate potable water through the collector, but closed loop systems use an antifreeze heat-transfer fluid loop (typically containing polypropylene glycol) to transfer heat from the collector to the potable water in the storage tank. Some systems also use a load-side heat exchanger between the potable water stream and the hot water in the tank.

The passive or thermosyphon systems rely on the natural circulation of water between the collector and the tank, or the heat exchanger in the tank. As passive systems do not rely on pumps and controllers, they do not require an electrical supply. They naturally modulate the circulation flow rate in phase with the radiation level, and are more reliable and have a longer life than pumped systems. Passive systems can also be built with inherent freeze resistance so they can be used in areas that are subject to extended periods at freezing temperatures.

### Thermosyphon systems

A thermosyphon system relies on the natural circulation of water between the collector and the tank or heat exchanger. To achieve circulation during the day and to limit reverse circulation at night, the tank must be above the collector. As water in the collector is heated, it rises naturally into the tank, while cooler water in the tank flows down to the bottom of the collector, causing circulation throughout the system. Thermosyphon systems can be designed with freeze protection devices ranging from dump valves or heaters in the bottom collector header for mild freeze areas, to inherent freeze resistance by using a natural circulation antifreeze closed loop, between the collector and the tank. Typical collector configurations include flat-plates

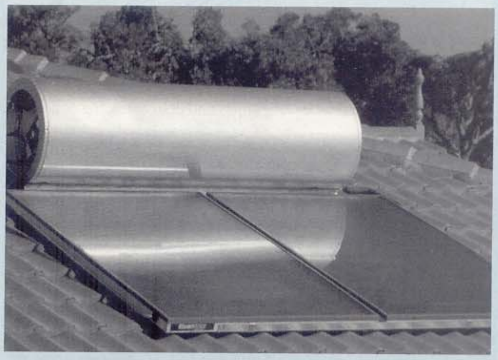

FIGURE 1. Thermosyphon flat-plate collectors with direct connection to a horizontal tank or connection through a heat exchanger for freeze protection

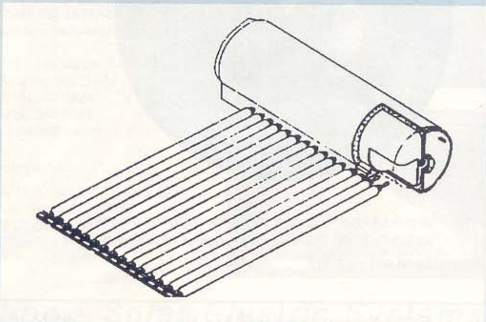

FIGURE 2. Thermosyphon evacuated tubular collectors with direct connection to a horizontal tank (Thermomax)

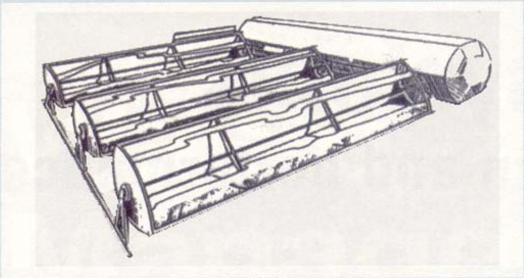

FIGURE 3. Parabolic trough collectors with the heat pipe absorber inserted directly into the base of a horizontal water tank (SunTrack)

(Figure 1), evacuated tubes (Figure 2) and concentrating collectors (Figure 3).

### Evacuated tube collector systems

Extensive development of evacuated tubes has led to the introduction of a range of evacuated tubular collectors and integral water heaters. In China, all-glass evacuated tubes are now produced in very large quantities (20 million in 2001), mainly for wet tube domestic water heaters (Figure 4). The wet tube concept, in which water is in contact with the glass tube, can only be used for low pressure water heating systems, as the tubes cannot withstand more than a few metres of water pressure. Evacuated tube collectors incorporating pressure tubing inside all-glass evacuated tubes are also in widespread use.

### Integral tank-collector systems

Integral systems combine the tank and collector into one unit. These systems are simple and effective. However, due to high heat loss at night, they only provide hot water during the day and early evening. The products range from simple glazed, low-pressure plastic tanks to high-quality steel tank systems with selective-surface coatings to minimize heat loss. Typical system configurations include single tank systems, progressive pipe systems and stationary concentrator systems. The main limitation with this system concept is that it is only a preheater, and hence must be connected in series with a conventional water heater if a 24-hour hot water supply is required.

## Active systems

In active systems, the heat-transfer fluid is pumped through the collectors. Active systems are usually more expensive and are less efficient than passive systems, particularly if antifreeze measures are required. Active systems are more difficult to retrofit in houses that do not have basements, because space must be found in the house for additional equipment.

### Open loop active systems

Open loop active systems circulate water directly from the tank through the collectors, as shown in Figure 5. This design is efficient

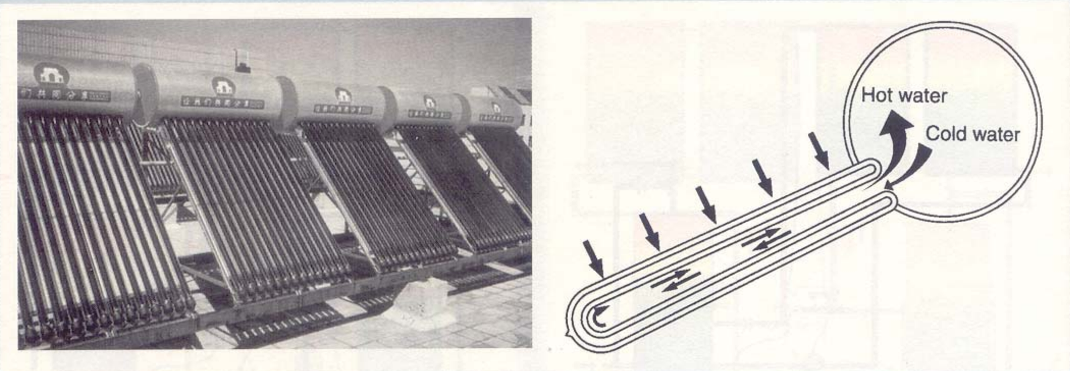


FIGURE 4. Thermosyphon evacuated tubular collectors with direct connection to a horizontal tank

and lowers operating costs, but is not appropriate if the water supply is hard, because calcium deposits quickly build up in the collector. Open loop active systems can be given limited freeze protection by running the pump when the collector temperature approaches zero. Such recirculation freeze protection should only be used for locations where freezing occurs a few times a year, as this protection mechanism dumps stored heat. Of course, when the power is out, the pump will not work and the system could freeze. To guard against this, a dump valve can be installed in the bottom of the collector, to provide additional protection in the event that the pump fails to operate to prevent freezing. A dump valve dribbles water out of the bottom of the collector when the collector temperature is below 5°C.

### Closed loop active systems

In a closed loop system, the heat-transfer fluid is pumped through the collectors and a heat exchanger is used to transfer heat from the collector loop to the water in the tank, as seen in Figures 6–8.

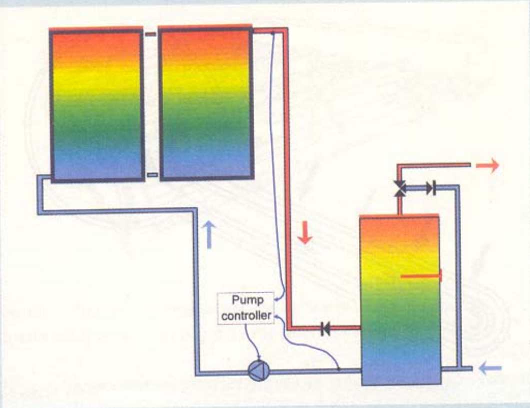


FIGURE 5. Open loop pumped circulation system

Closed loop glycol systems are popular in areas subject to extended freezing temperatures as they offer good freeze protection. Glycol antifreeze systems are more expensive to construct and install, and the glycol level must be checked yearly, and changed every few years, depending on glycol quality and system temperatures.

Drainback systems use water as the heat-transfer fluid in the collector loop, and gravity ensures the water drains back to the

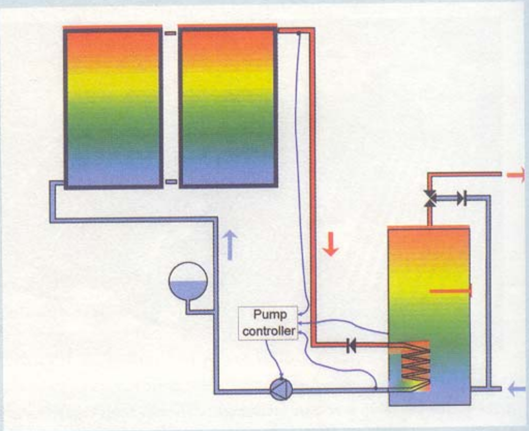


FIGURE 6. Closed loop pumped circulation solar water heater with internal coil heat exchanger

storage tank or an auxiliary tank when the circulation pump stops. This system provides a high level of protection, as it does not rely on valves or controllers that could fail under adverse freezing conditions. The disadvantage of this system is that a pump with high static lift capability is required in order to fill the collector when the system starts up.

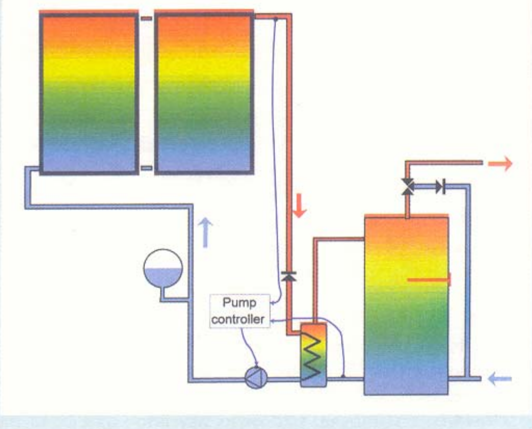


FIGURE 7. Closed loop pumped system with external collector loop heat exchanger and natural circulation in the tank loop

## Solar boosted heat pumps

The heat pump water heater concept has been extended to incorporate solar boosting of the heat pump evaporator. Solar boosted heat pumps are manufactured in a number of countries. The original system concept, proposed by Charters *et al.*,[1] was for a system with direct evaporation of the heat pump working fluid in the solar collector, as shown in Figure 9. This was a significant simplification from earlier designs, based on a solar

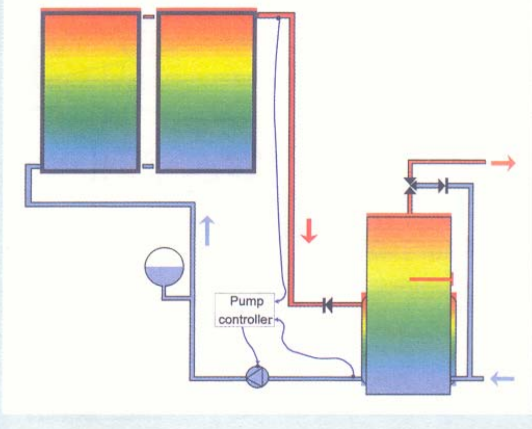


FIGURE 8. Closed loop pumped system with mantle heat exchanger

preheater in series with a heat pump. To minimize system costs and parasitic energy requirements, this system incorporates the heat pump condenser as a wrap-around heat exchanger on the water storage tank. The integration of the condenser into the tank eliminated the parasitic energy of the pump, used to transport heat from the heat pump condenser to the water storage tank in conventional solar heat pump configurations. The disadvantage of this system is that the condenser heat transfer

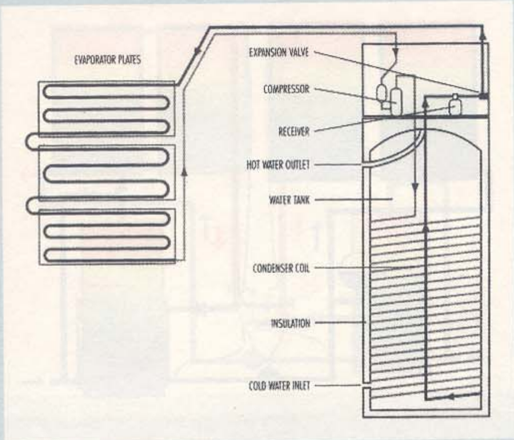


**FIGURE 9. Example of solar boosted heat pump water heater components (Quantum Energy Systems)**

is limited by free convection from the tank wall. By using a large heat transfer area in the tank, this penalty is minimized. The disadvantage of this system is that the heat pump refrigeration circuit must be evacuated and charged at the installation site.

**Positioning the collectors so that they receive maximum annual radiation does not necessarily result in maximum system effectiveness**

### Compact heat pump with solar boosting

Compact solar boosted heat pump systems have also been developed to reduce installation costs arising from the need for on-site charging of the refrigerant connections to the remote evaporator system. The compact system incorporates an evaporator mounted on the outside of the water tank with natural convection air circulation over the evaporator, as shown in Figure 10. This system can be installed outdoors in order to gain solar boosting.

However, a significant part of its operation may be in the conventional air-to-water heat pump mode.[2] This system is ideally suited for installation outdoors adjacent to ventilation ducts, so it can function as a solar collector and a waste heat recovery unit. The advantage of this system over a conventional air-to-water heat pump is that it does not have the parasitic energy of a conventional fan coil unit. The packaged system also has the advantage that all the components are assembled in the factory, and installation is simpler than with a conventional electric water heater since the unit does not require a high-power electrical connection, as the compressor motor power is typically only 500 W.

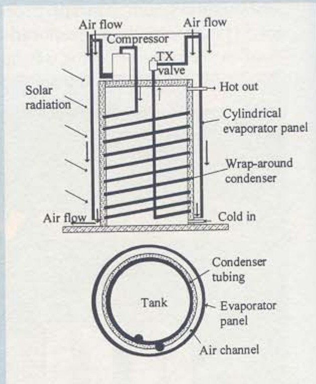


**FIGURE 10. Compact solar booster heat pump water heater components**

### Air-source heat pumps

Air-source heat pump water heaters used for domestic applications are manufactured in a number of countries. The majority of the energy output of an air-source heat pump is drawn from air passing over the evaporator coil, and hence these products are indirect solar water heating systems.

## Factors governing solar water heater performance

### Collector orientation and inclination

Variations in the performance of solar water heaters can occur when the orientation or inclination of the collector are less than ideal, due to two main factors – the radiation characteristics at the application site, and the seasonal load pattern for hot water use. Yet positioning the collectors so that they receive maximum annual radiation does not necessarily result in maximum SDHW effectiveness. For example, in summer, when

the hot water demand is low, the system may be collecting 'excess' energy. Also, evaluation of SDHW performance with a fixed volume delivery per day (or variations with season) will give an incorrect indication of 'clear day' performance, as the delivery temperature will be high, and a mixing valve or user-controlled mixing will significantly reduce the load volume on such days. Analysis of seasonal performance variation, with array orientation and inclination, should be carried out with realistic seasonal load patterns and should allow for a mixing valve in the system to modulate the load volume in response to tank temperature variations.

Figures 11–13 show examples of the results of such an analysis carried out on thermosyphon SDHW systems in Copenhagen (latitude 55.8°N), Sydney (34°S), and Singapore (1°N); in these applications, the summer energy delivery is 20% less than for winter, and the cold water temperature is equal to the average ambient temperature during the previous month. The shaded areas in these figures represent the zones of collector orientation and inclination that result in annual performance within 5% of the optimum. The variation of performance is relatively insensitive to collector orientation (azimuth) within ±50° of the north–south line for low latitudes, but becomes more significant

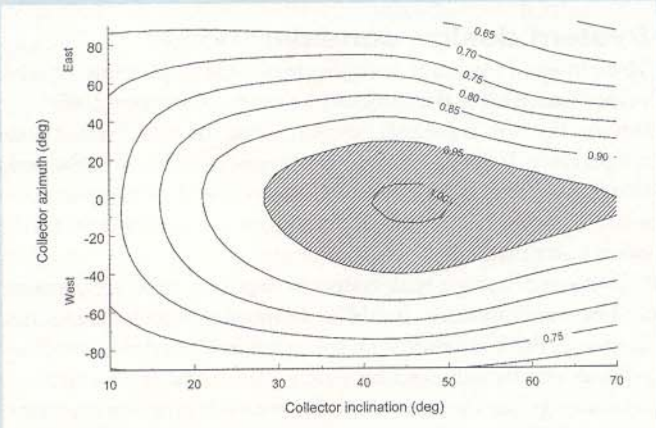


**FIGURE 11. Relative annual performance as a function of orientation (azimuth) and inclination of a thermosyphon SDHW system in Copenhagen (latitude = 55.8°N)**

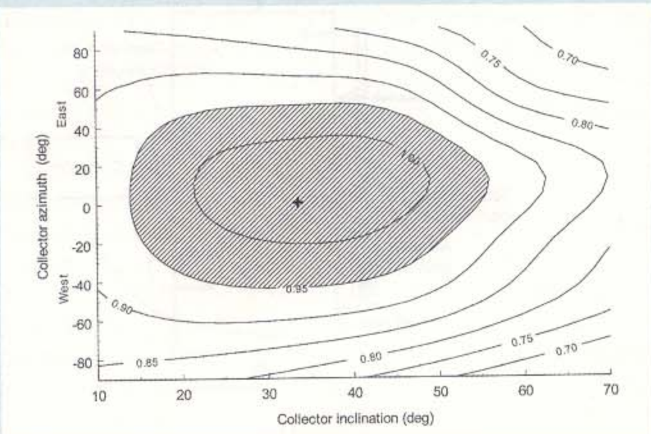


**FIGURE 12. Relative annual performance as a function of orientation (azimuth) and inclination of a thermosyphon SDHW system in Sydney (latitude = 33.6°S)**

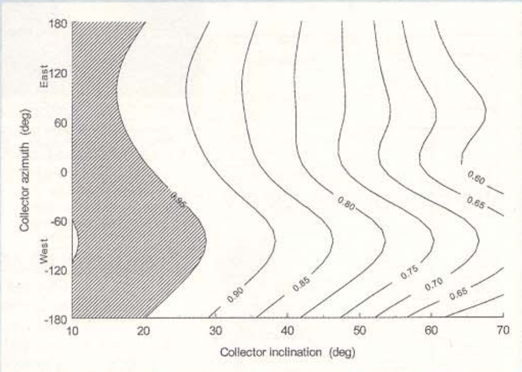


**FIGURE 13. Relative annual performance as a function of orientation (azimuth) and inclination of a thermosyphon SDHW system in Singapore (latitude = 1°N)**

at high latitudes (as shown for Copenhagen in Figure 11). For arrays facing the Equator (azimuth = 0), acceptable performance is obtained for inclinations within ±15° of the latitude angle. For locations close to the Equator, such as Singapore, performance is independent of orientation, provided the inclination is less than 20°, as shown in Figure 13.

### Flow rates in active systems

A high flow rate is often used in both open and closed loop pumped circulation systems, because heat transfer within the collector improves with increased flow rate. The disadvantage of high collector loop flow rates – in both open and closed loop systems – is that thermal stratification in the storage tank may be disturbed by the high flow, even if a heat exchanger is used between the collector and the tank. Specification of low collector loop flow rate in closed systems is often limited by the lack of suitable low-power pumps with sufficient static lift to fill the collector circuit.

The benefit of low flow operation is the promotion of thermal stratification in the storage tank. However, low flow rate is only one factor influencing stratification, and improved performance will only be achieved if all factors influencing stratification are considered. For example, if consideration is not given to minimizing the mixing of the hot input flow into the storage tank, then changing to low flow in the collector loop could reduce system performance. This interaction of factors is the reason conflicting results have been observed in some assessments of low flow systems. High flow systems can have varying degrees of stratification depending on whether there are heat exchangers in the collector loop or the load flow stream. Heat exchangers such as internal coils, full height mantles or external spiral tubing on the wall of the tank, all minimize mixing in the tank and give some stratification, even for high collector loop circulation rates. Maximum performance benefits can only be gained through a fully integrated low flow system design. The low flow design approach influences both system capital cost and operating. The most obvious impact is that a smaller, low power pump can be used. Piping to the collectors can be of smaller diameter and hence flexible, easier to install, and less expensive. Smaller tubes lower the thickness, and cost, of pipe insulation because the R-value is dependent on the ratio of outer diameter to inner diameter and not the absolute thickness of the insulation. Maximum benefit will be achieved in a low flow system if the following load matching principles are incorporated:

- flow in the collector loop in the range 0.2–0.4 litres/min $m^2$
- flow into the solar storage controlled to maximize stratification
- total daily flow through the collector on an average day matched to the daily load flow
- collector loop is designed to minimize pumping power.

## System design considerations

The most important requirement for optimum system performance is for the tank to be thermally stratified, with the top of the solar preheat section close to the desired load temperature. Whatever mechanism is used to add heat to the tank, there should be as little mixing as possible. As a corollary, the auxiliary input should be provided so as not to interfere with the operation of the solar part of the tank.

Division of a single tank system between the solar preheat zone and the auxiliary zone should be designed to match the required load and the availability of solar input. A variable auxiliary volume can be achieved by placing the auxiliary element, or auxiliary coil, in a side arm connection or side arm heat exchanger as shown in Figure 14.

The side arm heater can be used to provide a delivery capacity

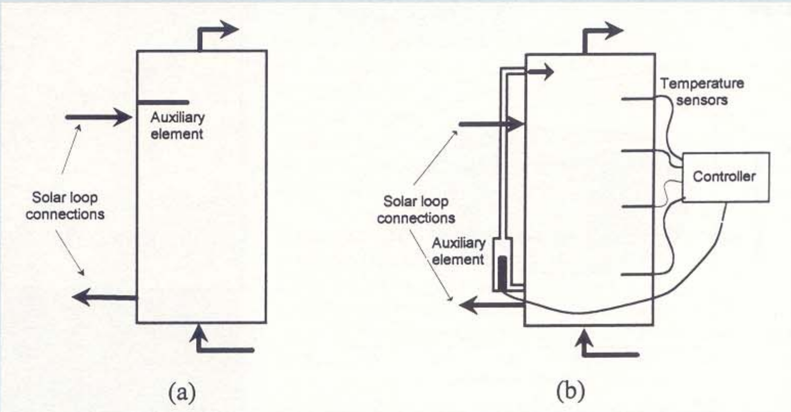


**FIGURE 14. Auxiliary heating element locations: (a) fixed auxiliary volume; (b) variable auxiliary volume**

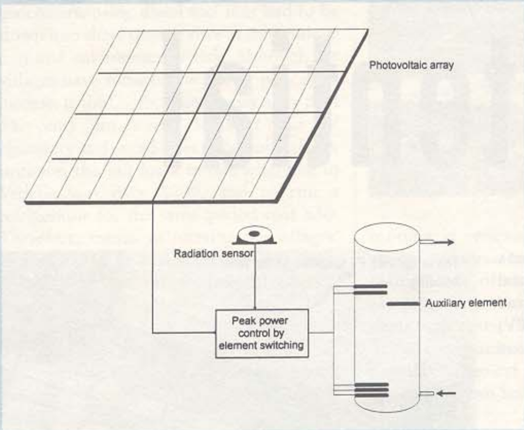


FIGURE 15. Photovoltaic electric water heater

that varies across the day to match the demand pattern of the user. In winter, the side arm auxiliary controller could be switched to provide a greater boost volume to match higher hot water demand. In summer, the boost volume could be reduced to allow greater solar contribution. A programmable controller could be used to maximize solar contribution while maintaining a delivery capacity across the day that matches a specified pattern. The load pattern could be set by the user or 'learned' by an intelligent controller.

The collector flow rate should be such that fluid is delivered to the tank at temperatures commensurate with the desired hot water temperature. The best algorithm to control this flow is not known, but low flow in pumped circulation systems works well if attention is paid to minimizing mixing in the tank. An undersized collector loop heat exchanger will raise both the collector supply and return temperatures, even with an adequate collector flow.

Pumps used in solar water heaters have low power requirements, so direct current pumps powered by small photovoltaic panels may be used. A PV pumping system acts as a fast sensor and controller. To avoid pumping when there is no useful output from the collector, the pump may be operated in conjunction with a differential temperature controller. The main advantage of a PV-powered pump is that it eliminates the need for an auxiliary power source to run the pump. By appropriate selection of the motor and PV array, it is possible to provide optimum flow circulation in the collector for a wide range of radiation intensities.[3,4]

## PV electric solar water heaters

Although the current cost of PV modules is extremely high, the concept of a PV-SDHW system (Figure 15) has been proposed and evaluated by Fanney and Dougherty[5,6] and Williams *et al.*[7] The advantage of a PV-SDHW system is that it eliminates the piping and associated heat loss of the liquid collector loop and it does not require freeze protection. A controller is used to set the electric element resistive load to achieve peak power tracking of the PV array; however, unlike other residential PV systems a PV-SDHW system does not require an inverter or a battery storage system. There are no roof penetrations and the installation is simple, although the collector area will be several times that required by a thermal collector. Superior system reliability would be expected relative to a pumped SDHW system with freeze protection. A PV-SDHW system would be more complex, and perhaps not as reliable as a thermosyphon system in temperate locations where freeze protection was not an issue. For such a system to be competitive with a pumped SDHW system, with freeze protection, the price of the PV modules is projected to have to fall below US$1.90 per Watt.

## Summary

There is currently very rapid expansion of markets for solar water heaters, particularly in China and Europe. Different product designs have been adopted in different areas to suit local requirements. The fastest growing technology is the water-in-glass evacuated tube solar water heater, which has become the most commonly used system in China. Other evacuated tube system configurations have been adopted in Europe. Solar water heater markets in warmer climates are likely to continue to be based on flat plate collector technology, while markets in colder areas may move towards evacuated tube collectors. The market development will hinge on the quality and cost of tubes available from the very large manufacturing facilities in China.

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*Graham L. Morrison is Professor of Mechanical Engineering at the School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, Australia.*
*Fax: +61 2 9663 1222*
*e-mail: g.morrison@unsw.edu.au*

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