Super-efficient hot water

Richard Keech explains how he combined an evacuated tube solar collector and a heat pump to make a high efficiency hybrid water heater.

On my three-bedroom Melbourne house I have what might be the most efficient solar hot water system around. In the year since installation it has performed extremely well, and I've learnt a lot along the way. This article will consider aspects of solar hot water design and rationale that led me to the system I have now. Then it will look at the system as built and the lessons after one year of operation. My design for the system brings together some ideas about what makes for a more sustainable hot water system. Some of these ideas challenge conventional wisdom on the subject.

The solar collector tilted at 64°. In summer the early morning and late afternoon sun actually heats the evacuated tubes from behind!

Crank it up

For hot water, the *Your Home Technical Manual* for example suggests to tilt the (north-facing) solar panels at an angle corresponding to the latitude of the location and "in some cases, it may be desirable to increase the angle somewhat to improve winter performance and reduce overheating in summer". Despite this, it's uncommon in my experience to see solar collectors tilted above 35°.

My interpretation of the situation is that it's more than merely "desirable in some cases"—it's really important to increase the tilt of solar collectors for hot water, but not PV. To appreciate why, we need to recognise the key difference between solar hot water and solar PV, namely, that solar hot water systems cannot make use of their surplus energy. Indeed excess summertime solar gain can be a problem as discussed in *ReNew 113 (DIY Solar Hot Water Cover* page 72). On the other hand, urban PV systems have the benefit that excess generation is simply exported to the grid.

Grid-connected PV systems are best configured for maximum annual solar gain. However, we need to apply a different rule of thumb for hot water—to configure for the maximum number of days with sufficient solar gain. This means cranking up the solar collectors to a much steeper angle. This is done to maximise solar gain in winter and to help reduce overheating problems in summer. To optimise for winter noon, the angle should be latitude plus 23.5°, which in Melbourne is 61°. Given that the angle of the sun is lower than its noon angle for most of the daylight hours, it follows that the collector angle should be even a little higher than this. I chose to tilt my collector at 64° from the horizontal.

Thinking differently about plumbing and stratification

The conventional way to hook up a roof-mounted solar collector to a ground-level tank is to have the solar hot-water return pipe connected to the top port of the storage tank. The thinking is that to do so maximises stratification, i.e. the tendency to have the heated water remain above and naturally separated from the cold water by simple convective action.

I'm of the opinion that this normal arrangement has two problems: too much stratification on hot days, and perversely it can actually lessen the stratification when it's really needed. So my preference is to bring the hot-water return in at the bottom of the tank, on the opposite side from the cold-water line to the solar collector.

Stratification example

Consider a cooler day with some useful sunshine. In the morning before occupants have their showers, the stored water remains hot from the previous day (say 60°C). Early showers take hot water from the top of the tank and replace it with cool water at the bottom of the tank (say 18°C). The hot water and the cold water regions remain separate, and the tank is said to be well stratified.

When the sun heats the collector sufficiently above the temperature at the bottom of the tank, the pump begins to deliver heated water to the tank. Being early in the day, and since there is a volume of cold water in the bottom of the tank, the heated water is not yet very warm, perhaps 28°C. If the water at 28°C is delivered to the top of the tank (by the conventional plumbing arrangement) it would dilute the 60°C water and lead to a rapid drop in temperature. If there is hot water demand during this time then there is the risk that the delivered water temperature will not be high enough without boosting.

If we deliver the heated water at the bottom of the tank at the opposite side to the cold water line, then natural convection will allow that water to rise to the top of the cool zone, but leave the well-stratified hot region of the tank largely undisturbed. The result is a much lower chance that the hot water delivery temperature is adversely affected. So, counter-intuitively, returning heated water to the top of the tank can diminish useful stratification.

The other benefit is that bringing hot water in at the bottom leads to a more uniform temperature through most of the tank. This is useful in two ways. First, when large amounts of hot water are demanded, there will be less chance of a sudden drop in delivered water temperature when the hot water layer is used up. So the need for high-power boosting is lessened. The second benefit of a more uniform temperature distribution relates to meeting bacterial safety standards discussed below.

The Legionella problem

It's long been a given in hot water service implementation that the tank temperature should be regulated to at least 60°C to ensure that Legionella bacteria are killed. This is embodied in Australian standard AS/NZS3500.4:2003 which says "Heated water shall be stored at a minimum temperature of 60°C, to inhibit the growth of Legionella bacteria."

Bacterial considerations aside, in normal domestic situations it would be unusual to need hot water above 45°C. Basic physics means that the higher the temperature difference between the tank and ambient, the higher the heat loss. So the higher the storage temperature, the greater the energy needs.

I set out to examine hot water and the risk of Legionella a bit more closely, to see if there was any way that one could legitimately control a hot water service at temperatures below 60°C. I contacted Standards Australia and found out that they haven't been sitting on their hands. An update to AS/NZS3500.4 is imminent at the time of writing. The draft new version of the standard says "Heated water shall be stored and delivered under conditions that avoid the likelihood of the growth of Legionella bacteria. This may be achieved by:

(a) storing heated water at a temperature above 60°C; or

(b) installing a water heater certified to AS 3498 (Australia only)."

It turns out that AS3498 provides for temperature regulation with a bit more finesse. The 60°C requirement is replaced by the requirement to provide a sterilising pulse of heat to the tank at least once a week.

Consider a day of 20°C. Storage of hot water at 42.5°C will involve storage heat losses half that of hot water at 65°C, all other things being equal. This is because the difference between the water and ambient is half as much in the 42.5°C case. So if, six days out of seven, water is stored at the lower temperature, then heat loss will be significantly reduced.

Heat-pump storage hot water unit showing the solar controller at the right-hand-side and insulated pipes to the collector.

The net result of this is that hot water services can be legitimately operated more efficiently by allowing lower storage temperatures without compromising bacterial safety obligations.

Hybrid solar plus heat pump

Putting these ideas together led me to design a solar hot water system based on the following criteria:

- mains gas should not be used
- over-size the tank to 'bank' solar energy over a couple of days of use
- the solar collector should be optimised for winter by tilting at an angle of latitude + ~25°
- control the temperature at less than 60°C most of the time
- use a bottom-return connection between the tank and the collector, which rules out tanks with only two ports.

My solar hot water system combines a 30-tube evacuated tube collector and a storage heat pump hot water unit. The heat pump uses a Quantum 340 litre system while the evacuated tubes are from Apricus. These are fitted together according to the principles described above.

As originally installed, the solar part of the installation was controlled conventionally and independent to the heat pump. For the first year of operation, this required the heat pump to be turned on manually based on monitoring temperature. Since then I have retrofitted a SolaStat-ST controller which is capable of controlling both electric and solar elements together.

The initial system installation was done by commercial solar installers to my specifications. No special customisation or equipment was required, since the novelty of the configuration was really in using the heat pump unit in place of the storage tank in a conventional solar hot water arrangement. Despite this, finding an installer to do it wasn't easy.

The pipe insulation provided at installation was meagre. Ten millimetre thick pipe insulation was provided, which I gather is common practice. I boosted this to 23mm plus added aluminium tape to reduce pipe losses and lessen the weathering of the insulation.

In operation

The system has delivered hot water successfully for over a year now. Key observations have been:

- Very high collector angle does not compromise summer performance. The system still gets hot enough to go into stagnation in mid summer
- Tank capacity is enough for about three days of family use, so the idea of 'banking' hot water seems to work well to cover for days of less sunlight
- Operation without boosting was achieved for 299 out of 364 days, i.e. equivalent to 10 out of 12 months.

Energy and temperature measurements were taken during the first year to gauge the performance. This allowed assessment of electrical energy used for both pumping and boosting.

Performance results

In the period studied (mid-August 2009 to mid-August 2010), total electrical energy required was 145kWh (523MJ). Of this, 74% was for heat pump boost, 7% for the controller and 19% for the pump. To put this in perspective, a 5-Star gas hot water unit is defined as one that requires less than 20,808MJ per annum in a standard test. My energy requirement, is therefore 97.5% less, or about one fortieth. This was achieved despite 2010 being relatively wet and overcast.

Conclusions

I've shown that it's possible to radically reduce mains energy requirements for domestic hot water using off-the-shelf components in a novel way. We are used to solar hot water typically giving a 2:1 or 3:1 reduction in mains energy demand. I've shown that greater than 30:1 is possible, even without a great solar climate.

The goal of trying to maximise the number of days with sufficient solar gain, by elevating the collectors to a much higher angle, seems to have paid off. Trading off excess summertime solar gain for much-needed winter solar gain is the key to the improved performance.

If I were to do this again, I'd probably make the collector angle even steeper, and dispense with the expensive heat pump and use a conventional electric hot water because the boosting requirements can be made so low that the extra efficiency of the heat pump becomes lost in a diminishing return. The only problem is the government's plan to phase out electric hot water services, which is another discussion altogether. ✲

Gas is not green!

Current advice on 'green' hot water normally involves gas boosting. On the other hand, my approach has been informed by idea that gas is not the sustainable choice it's often made out to be. When completely combusted, the emission intensity of methane, the main component in natural gas, is much less than that of brown coal. While that is a good thing, direct emissions from burning methane are still non-trivial. There are also significant global warming emissions in production and distribution of gas. Un-burned methane is (depending on the time frame and how you count it) at least twenty times more potent as a greenhouse gas than CO_2, so it doesn't take much leakage to make a significant dent in methane's supposed green credentials.

There's no such thing as zero-emission mains gas. However zero-emissions electricity is readily available through the GreenPower scheme, and the potential exists for significant additional non-emitting energy to be added to the grid. To tackle climate change we need to aim for zero emissions, not merely 'low' emissions. Accordingly, I chose to create a system that did not need gas.