The Centenary of Solar Collectors for Heating Water

Brian Norton

Dublin Energy Lab, Dublin Institute of Technology, Dublin, Ireland,
E-mail: president@dit.ie

Abstract: After over a century of system development, solar water heating can be considered to be an established mature technology. In seeking to achieve economic viability systems have been developed, for specific applications and climatic contexts that produce often optimal hot water per unit cost. The development of solar water heaters is discussed with the emphasis on overall systems, their features, characteristics and performance though some key aspects of component development are also outlined.

Keywords: *Solar water heating, Thermosyphon, Solar Collector*

1. Origins

The solar water heater first manufactured commercially was an integral collector storage unit patented in 1891, in which, the hot water store absorbs solar energy directly usually from beneath a glazed aperture. Nocturnal losses to ambient usually led to water heated by the sun on one day being luke-warm early the next day. As this reduced both user convenience and the overall solar fraction and led to thermosyphon solar water heaters with diurnal heat storage displacing integral collector storage water heaters. [1.2] The thermosyphon solar water heater, was patented in 1910 by Bailey [3], used flat-plate collectors in which a single serpentine tube removed heat from the absorber plate. More modern header-and-riser absorber tube arrangements emerged later. [4] This paper explores the characteristics of the solar water heater types that have emerged over the centenary since Bailey patented the first solar water heater with separate solar collector.

2. Thermosyphon Solar Water Heaters

In a thermosyphon solar water heater hot water in a solar-heated collector is located beneath cooler water in a store. The difference in the densities induces gravity-driven buoyancy forces in a closed circuit comprising the solar collector, hot-water store (or in an indirect system, a heat-exchanger) and the associated pipework. The height difference provides a nocturnal counter driving pressure that prevents reverse circulation of hot water from the store to a cold collector [3]. Arranging pipework [5] or the tank shape [2] can also create an intermediate counter pressure to a reverse buoyant flow. Low forward-flow resistance non-return valves have unproven long-term practical reliability [6]. Thermosyphon solar heaters are classified broadly as either close-coupled or distributed [2]. In both types the solar heated fluid can either be potable water circulated directly to the store [7] or an aqueous anti-freeze solution [8] that flows through a heat-exchanger immersed in, or forming a manifold around, the hot water store. In regions with “hard” water, use of soft water as the anti-freeze solvent avoids calcium carbonate scale deposits restricting flow and inhibiting heat transfer.

Evacuated tube thermosyphon solar water heaters have two principal forms. An indirect “dry” absorber heat is transferred from a closed heat pipe [9] to a bayonet heat exchanger protruding from the glass envelope to an aqueous propylene glycol solution (for an indirect secondary circuit) or water (for a direct secondary circuit) conveyed buoyantly respectively to a heat exchanger in the store or to the store directly. In a “wet” evacuated tube, water circulates in a thermosyphon comprised of the evacuated tube and the store. Inserted directly into sockets in the store, flow-through "wet" evacuated tube collectors avoid the heat exchanger efficiency losses of closed "dry" collectors. Over fifteen million thermosyphon installations in China employ wet type evacuated tubes. Though exported from China to other regions, internationally such systems have not yet displaced close-coupled flat-plate collector thermosyphon units.

Pumped circulation solar water heaters do not generally either provide more hot water or heat water more efficiently than a comparable thermosyphon system [2]. However pumped systems have a significant advantage of layout flexibility over thermosyphons; only collectors need be external to the building and the roof / attic does not need to sustain the weight of a hot water store. Larger installations are thus easier. To avoid cooling water from the hot water store, the pump ceases operation at night and during periods of collector net heat loss. To achieve this, temperature sensors located usually at the collector's inlet and outlet signal a controller that activates the pump. In most systems the pump is activated simply by specified collector temperature difference. In systems using a photovoltaic-powered circulation pump, the pump operates only when the solar energy intensity is sufficient to meet the power requirement of an optimally-selected pump. For most pumped-circulation systems, the collectors are roof mounted through novel wall-mounted systems have been proposed. Very-large scale solar district heating applications have used free-standing collector arrays. As a high water temperature is not sought, unglazed flat plate collectors are used to heat swimming pools often with simple arrangements of black plastic pipes. Swimming pool heating is currently the predominant use of solar water heating in the USA, Canada and Australia. Systems almost always use pumped circulation and together with the pool itself collectors are drained in winter in locations at higher latitudes.

Solar combisystems satisfy both part of a building's space heating demand and part of the domestic hot water consumption. High energy savings can ensue when a well-insulated thermally-stratified small capacity auxiliary heat store operates at a low set-point temperature. In tank-in-tank solar combisystems, a domestic hot water tank is integrated into the space heating hot water store: solar heat is transferred by an internal spiral heat exchanger located low in the tank. Domestic hot water is withdrawn directly from domestic hot water tank in the store. Alternatively a "bikini" tank uses two separate mantles encircling circumferentially the hot water tank at upper and lower levels, to circulate domestic hot water and solar heated water respectively both transferring heat to the space heating water with domestic hot water being withdrawn directly from the tank.

3. Novel Systems

To compete with solar water heaters with separate collectors and stores, integrated collector storage solar water heater designs have evolved to enhance insolation collection whilst reducing heat losses [10]. Using a heat retaining vessel consisting of an outer absorbing section and a perforated inner sleeve with a low thermal mass [11], enable flow from the outer channel to the inner store during collection periods but reduce flow through increased resistance, during non-collection periods. Experimental investigations [12-14] have shown using heat retaining vessels increase collection and improve heat retention. Two-phase transfer of heat from the solar collector to the store avoids scaling, fouling and the need for freeze protection, with suitable fluids, corrosion is far more limited than with aqueous systems. Working fluids such as Acetone, R134a and R410A are all low cost and available readily. Though acetone obviates the use of high pressures, it is flammable. R134a provides similar thermal performance, but requires a lower operating pressure R410A.

Heat provided by solar collectors may be used to evaporate the working fluid in the evaporator of a heat pump that transfers heat from a colder reservoir to a warmer reservoir.

Such systems are sometimes referred to as Combi^{+}. During compression the temperature of the heat pump working fluid increases to well above the temperature provided by the solar collector. During condensation, heat is rejected at a higher temperature to hot water store.

Photovoltaic solar water heating ensues when electricity from a photovoltaic array is dissipated as heat from a resistive heater immersed in the hot water store. The maximum power point of the photovoltaic array's current-voltage characteristic is maintained by varying optimally the electrical load imposed by the heating element. Solar energy conversion efficiencies of photovoltaic systems are generally lower (typically a factor of two or greater) that of solar thermal collectors. For a photovoltaic solar water heater the collection area is thus over twice that for a solar thermal water heater. The cost per unit area of photovoltaic cells is also higher currently than for solar thermal collectors. As large areas of a more expensive solar energy collection component are therefore necessary, photovoltaic solar water heaters are not competitive economically with solar thermal systems. However as only a cable connects the heating element in the store to the photovoltaic array, installation is simple and use of electricity to transfer energy obviates any need for mains water pressure reduction and/or freeze protection. Many building integrated photovoltaic systems [18] act as embedded generators that supply a grid [16]. Where photovoltaic-to-grid feed–in tariffs for electricity sold to the grid are not in place or do not provide a sufficient return on investment, the best use of building-integrated photovoltaic energy excess to the contemporaneous building electrical load is often to heat water. Indeed this prevails almost inadvertantly where instantaneous electric water heaters in a building supplied with photovoltaic electricity.

4. Solar Water Heater Taxonomy

The method(s) used to drive fluid flow, the fluid(s) used and the extent that a particular system is a single factory-built item prior to installation distinguish each principal generic solar water heater type. The scope for building integration, installation constraints and adaptation to climatic factors have also led to the current set of available types. A classification of solar water heaters based on key attributes is provided in Table 1. Both solar heated air-to-water systems and the use of photovoltaics specifically for water heating are uncommon.

				Hot-water store	**Prevention of nocturnal reverse thermosyphon**	**Collector Freeze protection**	**Position of store**		**Installation**	**Collector type**
							Relative to collector	Relative to building		
Hydronic	**Integral Collector Storage**			Single or multiple cylindrical usually horizontal. Plastic pillow or bags	Hot water withdrawal. Double glazing. Movable aperture installation.	Heat retained in thermal mass of the store	Same item	On roof exterior	Installed as a complete factory – built unit	Integral
	Thermosyphon	Close-coupled	Single phase	Horizontal cylindrical	Height of collector above store. Pipework arrangement.	Indirect. Drained.	Directly above			Evacuated tube. Flat-plate.
			Two phase		Cessation of fluid evaporation					
		Distributed		Vertical cylindrical	Height difference between collector and store	Indirect	Above	Inside loftspace	Assembled from components during installation	Photovoltaic / Thermal.
	Pumped	Solely Hot water		Vertical cylindrical	Non-return valve	indirect	Below	Variety of possible locations inside building		
		Combisystem: space and water heating		Vertical tank-in-tanks. Bikini tanks	Flow resistance of pipework and stationary pump					
		Solar-assisted heat pump (Combi $^{+}$)		Vertical cylindrical						
		Swimming pool heating		Swimming pool		Outdoor pool collectors drained in freezing weather	Pool usually located below	Solar heated pools are indoor and outdoor		Unglazed. Glazed flat plate.
Aeolic	Solar Heated Air			An air-to-water heating exchanger	Unnecessary		Various			Air-heating
Electric	Photovoltaic			Vertical cylindrical			Any	Interior	Water heating is an optional use of installed photovoltaic electricity	Photovoltaic

Table 1. Predominant combinations of attributes distinguishing different generic solar water heaters

5. Freeze protection

Water freezing in the collector incurs costs that adversely affect economic viability and consumer confidence. The cost of replacing a collector can be dwarfed if there is significant water damage to a building. Evacuation of collector tubes, multiple glazing layers and transparent insulation materials can provide collector freeze protection. Thermal mass can provide significant freeze protection for integral pressure solar water heaters [17]. Systems may also be drained in winter passing solar heated air through an air-to-water heat exchanger obviates the need for freeze protection. Air heating collectors are lighter and require less specialist installation expertise, however their lower efficiency and significant heat exchanger losses gives rise to large collector areas.

The most common protection against freezing within the collector pipework is the use of an aqueous glycol solution flowing in a closed loop comprised of the collector, a heat exchanger, and the associated pipework. The cost of automated nor manually-operated drain valves is avoided but more importantly, a glycol-filled indirect system can produce warm water in winter in maritime temperate climates, unlike a drained down system. This advantage is counteracted in summer by the lower thermal efficiency of an indirect system when compared with a direct one. For thermosyphons, the sources of indirect system's relative inefficiency are [8]; (i) higher viscosity of aqueous glycol solutions (compared with water) reducing the natural-circulation flow rate, (ii) additional flow resistance introduced by the heat exchanger, (iii) heat transfer resistance in the heat exchanger, and (iv) lower specific heat capacity of the heat transfer fluid compared with water. For a particular system in London, England [8], the optimum aqueous propylene-glycol concentration has been shown to be 25%, With this optimum solution an indirect system operated throughout the year provides a solar fraction approximately 12% greater than that from a direct system used from March to October that is drained-down in winter.

6. System specification

A wide variety of methodologies are available for sizing of system components and determining optimal operating parameters [18-23]. Utilizability approches are based on determining a minimum threshold insolation at which the collector solar heat gain and heat loss correspond at a particular ambient temperature. The collector only provides a useful heat output above this insolation. Hourly utilizability is the fraction of hourly incident insolation that can be converted to heat by a collector with ideal heat removal and no optical losses. All solar collectors have inherent heat losses (otherwise there would be no threshold insolation), so utilizability is always less than one. Utilizability can be related to statistical probabilities associated with diurnal and annual patterns of insolation [19, 21] producing expressions to which specific collector parameters can be attached. The generalised expressions then derived for the hot water produced are useful in initial conceptual stages of design, but limited by the accuracy of underlying insolation correlations and their applicability new locations/systems.

Using extensive detailed simulations, design charts have been produced [24, 25] that relate a normalised solar energy input to a similarly parameterised output for a given system configuration. The accuracy depends on how closely the putative system layout and component specifications conform to the system from which correlations were derived. Simplified analyses maintain the underlying physical basis for the relationships between parameters that is lost when correlations are derived using polynomial curve fits. Semi-analytical simulation use detailed numerical models. However rather than undertaking hour-by-hour calculations using insolation, ambient temperature and load data, in this approach sinusoidal and linear functions are used in semi-analytical simulations to describe the insolation and load respectively. These approaches have been superseded by hour-by-hour analysis as suitable computing resources have become available widely [26]. The solar energy system simulation software used most commonly is TRNSYS [27] either in its widely-available freeware form or as a kernel accessed through a proprietary graphical user interface. It includes ordinary differential and algebraic equations that describe each system component and a differential equation solver. TRNSYS is ubiquitous due to (i) initial dissemination via a seminal highly regarded text on solar heating [2], (ii) a modular structure of system component interactions, (iii) many available component models and (iv) users can develop programs to simulate novel components. With appropriate hourly insolation and ambient temperature data and a realistic description of pattern/volume of hot water load, simulation tools such as TRNSYS can provide valid performance predictions. Use of simulation software is generally (i) detailed design of large-scale systems, (ii) developing design correlations or (iii) addressing research issues in systems and components.

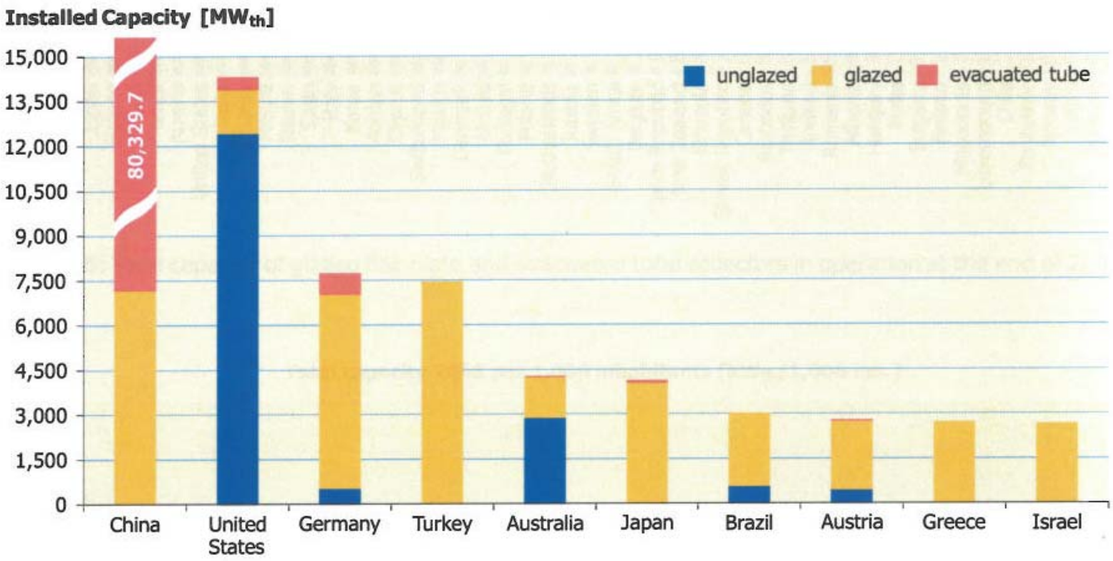

Fig 1. Global distribution of solar collectors by type in 2008 in the 10 leading countries (Weiss and Mauthner, 2010)

7. Conclusion

The current deployment [28] of each type of solar water heater varies globally depending on the price of displaced fuels; climate, [29-30] and commercial availability. From the global number and distribution of installations in 2003 shown in figure 1 it can be seen that where swimming pool heating is the dominant form of solar water heating as in the USA and Australia, unglazed collectors predominate. In marked contrast wet-type evacuated tube for domestic hot water are becoming ubiqiutous in China. In some countries, market stimulation and maintenance measures such as supportive building regulations, self-installer initiatives, building regulations and codes and/or various financial incentives have been or remain important. In many countries there remains considerable scope for greater adoption of solar domestic water heating.

Acknowledgements

Solar energy research at Dublin Institute of Technology is supported by Science Foundation Ireland through grants 06/RFP/ENE025 and 07/RFP/ENEF719. Support from the Commission of the European Union, Enterprise Ireland and the Sustainable Energy Authority of Ireland is also gratefully acknowledged.

References

[1] Butti K. and Perlin J., (1980) A Golden Thread. Van Nostrand Reinhold Co., New York, USA.

[2] Norton B and Probert SD, (1986). Thermosyphon solar energy water heaters. Advances in Solar Energy, 3, 125-170.

[3] Bailey, W.J. (1910), Solar Heater, US Patent 936079

[4] Brooks, F.A. (1939). Use of Solar Energy for Heating Water, Smithsonian Report for 1939, Smithsonian Institution, Washington D.C. USA. 157.

[5] Norton B. and S.D. Probert, (1983) Achieving Thermal Rectification in Natural-Circulation Solar-Energy Water Heaters, Applied Energy, 14, 211-225.

[6] Norton B. and S.D. Probert, (1984). Measured Performances of Natural-Circulation Solar Energy Water Heaters, Applied Energy, 16, 1-26.

[7] Eames P.C. and Norton B. (1998). The effect of tank geometry on thermally stratified sensible heat storage subject to low Reynolds number flows. International Journal of Heat and Mass Transfer, 41, 2131-2142

[8] Norton, B. and J.E.J. Edmonds, (1991). Aqueous propylene glycol concentrations for the freeze protection of thermosyphon solar energy water heaters, Solar Energy, 47, 5, 375-382.

[9] Tabassum S.A., B. Norton and S.D. Probert, (1988). Heat Removal from a Solar-Energy Collector with a Heat-Pipe Absorber, Solar and Wind Technology, 5, 141-145.

[10] Smyth M., P.C. Eames and B. Norton (2006). Integrated Collector Storage Solar Water Heaters, Renewable and Sustainable Energy Reviews, 10, 503-538.

[11] Smyth M, Eames PC and Norton B, (1999). A comparative performance rating for an integrated solar collector/storage vessel with inner sleeves to increase heat retention. Solar Energy, 66, 4, 291-303.

[12] Smyth M, Eames PC and Norton B, (2001b). Annual performance of heat retaining Integrated Collector/Storage Solar Water Heaters in a Northern maritime climate. Solar Energy, 70, 5, 391–401.

[13] [13] Smyth M, Eames PC and Norton B, (2003). Heat retaining Integrated Collector/Storage Solar Water Heaters. Solar Energy, 75, 27–34.

[14] Smyth M., P. McGarrigle, P.C. Eames and B. Norton (2005), Experimental comparison of alternative convection suppression arrangements for concentrating integral collector storage solar water heaters, Solar Energy 78, 223-233.

[15] Norton B., Eames P.C., Mallick T.K., Huang M.J., McCormack S.J. Mondol J.D. and Yohanis, Y.G. (2011) Enhancing the performance of building integrated photovoltaics, Solar Energy, Available on-line.

[16] Mondol, J.D., Yohanis, Y.G. and Norton, B. (2009) Optimising the economic viability of grid-converted photovoltaic systems, Applied Energy, 86, 985-999.

[17] Smyth M, Eames PC and Norton B, (2001a). Evaluation of a freeze resistant Integrated Collector/Storage Solar Water Heater (ICSSWH) for Northern Europe. Applied Energy, 68, 265–274.

[18] Rabl, A. (1985) Active Solar Collectors and their Application, Oxford University Press.

[19] Reddy, T.A. (1987). The Design and Sizing of Active Solar Thermal Systems, Clarendon Press, Oxford.

[20] Hobson P.A. and B. Norton, (1988). Verified Accurate Performance Simulation Model of Direct Thermosyphon Solar-Energy Water Heaters, ASME J. of Solar Engineering, 110, 282-292.

[21] Duffie J.A. and Beckman W.A. (1991) Solar Engineering of Thermal Processes. 2nd Ed. Wiley lnterscience, New York.

[22] Norton B., (1992) Solar Energy Thermal Technology, Springer-Verlag, Heidelburg, Germany.

[23] Norton B., J.E.J. Edmonds and E. Kovolos, (1992). Dynamic simulation of indirect thermosyphon solar energy water heaters, Renewable Energy, 2, 283-297.

[24] Norton B., (1995). A Generalised Dimensionless Grouped Parameter Method for Characterising Generic Types of Solar Energy Water Heaters, Applied Energy, 52, 511-517.

[25] Hobson PA and Norton B, (1988). A design nomogram for direct thermosyphon solar-energy water heaters. Solar Energy, 43, 85-93

[26] Norton B., P.C. Eames and S.N.G. Lo, (2001). Alternative Approaches to Thermosyphon Solar-Energy Water Heater Performance Analysis and Characterisation, Renewable and Sustainable Energy Reviews, 5, 79-96.

[27] Klein, S.A. et al (1996) TRNSYS: a transient systems simulation program, Version 14.2, Solar Energy Laboratory, University of Wisconsin, Madison.

[28] Weiss, W. and Mauthner (2010) Solar heat worldwide, Report of the International Energy Agency, Solar Heating and Cooling Programme.

[29] Yohanis Y G, O Popel, S Frid and B Norton (2006), Geographic Variation of Solar Water Heater Performance in Europe, Proceedings of the Institution of Mechanical Engineers, Part A, Journal of Power and Energy: 220, 395-407.

[30] Yohanis Y.G., O. Popel, S.E. Frid and B. Norton (2006) The annual number of days that solar heated water satisfies a specified demand temperature, Solar Energy. 80, 1021-1030.