Solar Water Heating Report

UCLA California Center for Sustainable Communities

Executive Summary

Reducing greenhouse gas emissions from the residential housing sector is an important part of California's attempt to shrink its carbon footprint, and prioritizing the most carbon intensive end-uses is essential to success. Residential water heating in California represents a quarter of household energy consumption, and the vast majority of residences use natural gas to heat water. Substantial energy savings can be realized if the share of renewable energy used to heat water were increased. This analysis explores the potential of community scale solar water heating systems to reduce residential natural gas consumption and generate energy savings.

The *Solar Water Heating Report* is the first part of the larger analysis. This report reviews the available solar thermal technologies and system types for community scale solar water heating systems. The resulting community scale system design based on climatic conditions, energy storage requirements, applicable building and energy efficiency codes, and cost. Based on these considerations, community scale systems considered in this analysis will be closed, active systems with flat plate collector arrays. Determination of basic system characteristics is a prerequisite for estimating their potential energy savings.

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1 Introduction

This report fulfills the Part 1 of Task 2 in the Community-Scale Solar Water Heating Project scope of work. *The Solar Hot Water Heating Report* is the first deliverable of Task 2.

The goals of this task are to review existing solar water heating technologies and systems, and establish the basic system design and construction requirements for community-scale solar water heating systems in Southern California. This report also assesses obstacles in applicable product, building, and land use codes for solar thermal systems. The report concludes with recommendations for appropriate component technologies and a basic system design for community-scale solar water heating systems in Los Angeles County.

1.1 Background

Limited availability of natural gas and abundant sunshine made solar water heating (SWH) systems an attractive choice for consumers during the end of the 19th and early 20th centuries.[1] Prior to the 1930s, a limited natural gas distribution network and high energy prices drove demand for domestic solar water heating systems. In 1897, one-third of homes in Pasadena had solar water heaters.[2] In the next several decades thousands of additional units were installed in California.[3,4] Consumers could heat water year-round without having to use a stove, saving fuel and keeping residences cooler during the summer months.[5]

During the 1930s, falling natural gas prices, urbanization, and incentives for consumers to switch to gas water heaters led to the displacement of solar thermal technology from the domestic market.[6] Fluctuations in energy prices during the 1970s and 1980s had a modest positive impact on demand for solar thermal, but as of 2009 more than 90% of households in California have gas or electric water heaters.[7]

1.2 Natural Gas Consumption for Residential Water Heating

California's natural gas consumption patterns indicate that diminishing the amount of natural gas used for residential water heating is an effective strategy for reducing greenhouse gas emissions from the residential housing sector. Table 1 shows that

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[1] Florida Solar Energy Center. (2006). Solar Water and Pool Heating Manual. *Solar Water and Pool Heating Manual*, (January). Retrieved from http://www.fsec.ucf.edu

[2] Islam, M. R., Sumathy, K., & Khan, S. U. (2012). Solar water heating systems and their market trends. https://doi.org/10.1016/j.rser.2012.09.011

[3] Denholm, P. (2007). The Technical Potential of Solar Water Heating to Reduce Fossil Fuel Use and Greenhouse Gas Emissions in the United States the Technical Potential of Solar Water Heating to Reduce Fossil Fuel Use and Greenhouse Gas Emissions in the United States, (March), 21. https://doi.org/NREL/TP-640-41157

[4] Islam, M. R., Sumathy, K., & Khan, S. U. (2012). Solar water heating systems and their market trends. https://doi.org/10.1016/j.rser.2012.09.011

[5] Florida Solar Energy Center. (2006). Solar Water and Pool Heating Manual. *Solar Water and Pool Heating Manual*, (January). Retrieved from http://www.fsec.ucf.edu

[6] *Ibid.*

[7] 2009 California Residential Appliance Saturation Study, KEMA Inc.

residential consumption represents approximately one-fifth of all natural gas deliveries statewide.

Table 1: Natural Gas Deliveries by Consumption Category 1997-2016 (MMft³)

Consumption Category	Volume of Natural Gas Delivered (MMft^3)	Percentage of Total Gas Deliveries
Residential	9,763,279	21.63%
Commercial	4,915,750	10.89%
Industrial	14,929,914	33.08%
Vehicle Fuel	184,247	0.41%
Electric Power	15,340,675	33.99%
Total Deliveries	45,133,865	100.00%

While water heating accounts for around 25% of total energy end use in residential buildings, water heating accounts for around 49% of residential natural gas consumption[9,10]. Additionally, 87% of residential buildings in California have gas water heaters, making residential water heating a major source of natural gas consumption.[11] Figure 1 shows annual natural gas consumption in residential buildings for the three largest natural gas utility providers in California, broken down by water heating, space heating, and general base use.[12] Figure 2 shows statewide residential natural gas consumption by end-use.[13] The proportion of total residential consumption represented by water heating suggests that a transition to a renewable sources of heat can yield significant energy savings and reduce greenhouse gas emissions.

[8] U.S. Energy Information Administration. (2017). *California Natural Gas Consumption by End Use 1997-2016 [Data set]*. Retrieved from: https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm

[9] U.S. Energy Information Administration. (2009). *2009 Residential Energy Consumption Survey [Data set]*. Retrieved from: https://www.eia.gov/consumption/residential/data/2009/index.php?view=microdata

[10] Denholm, P. (2007). The Technical Potential of Solar Water Heating to Reduce Fossil Fuel Use and Greenhouse Gas Emissions in the United States The Technical Potential of Solar Water Heating to Reduce Fossil Fuel Use and Greenhouse Gas Emissions in the United States, (March), 21. https://doi.org/NREL/TP-640-41157

[11] 2009 California Residential Appliance Saturation Study, KEMA Inc.

[12] *Ibid.*

[13] *Ibid.*

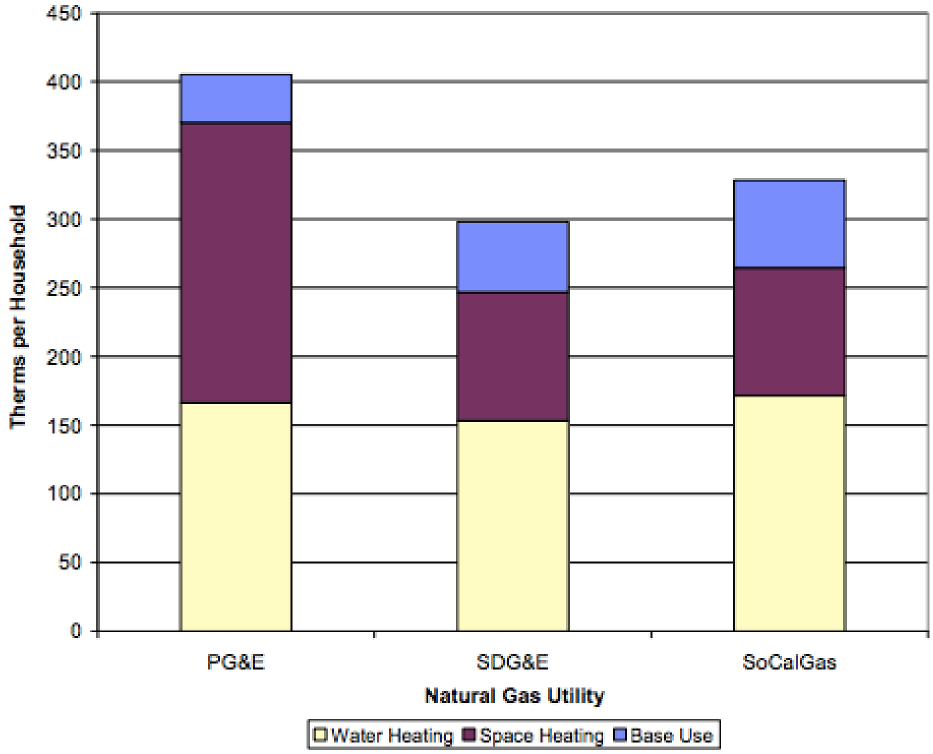
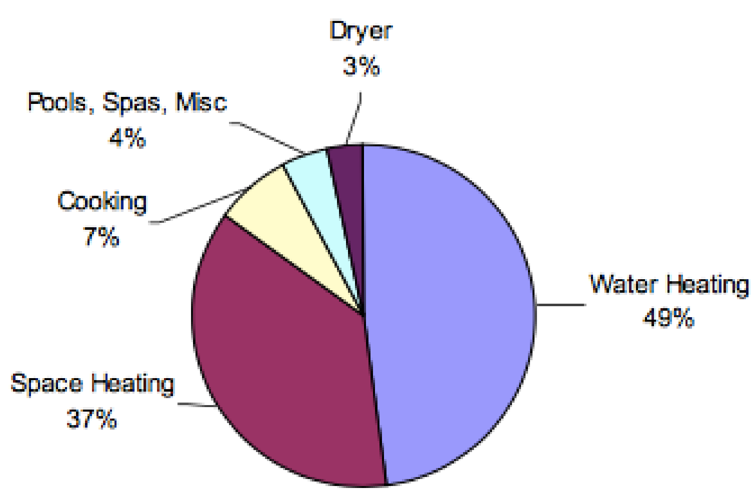


Figure 1: Residential natural gas consumption by for the three largest natural gas utilities in California.[14]

Figure 2



[14] *Ibid.*

[15] *Ibid.*

1.3 Community Scale Approach to Solar Hot Water

This report focuses on the energy savings and environmental benefits of community-scale solar water heating systems. In this context, “community-scale” describes both the size of the system and an adherence to a set of design principles. Community scale systems occupy an intermediate space between the domestic and utility scales. This report defines community scale systems as those able to meet the hot water demands of tens of residential buildings up to hundreds of residential units with greater that the minimum solar fraction required by law.

Community scale energy systems are intended to make maximally efficient use of local resources where possible and create a range of options for residents to contribute to its operation. According to the CEC and National Renewable Energy Laboratory (NREL), community scale solar energy projects should include the following considerations.[16, 17]

- Primary Considerations
    - Make economically optimum use of local space and resources when and where possible.
    - Develop community scale energy infrastructure in a socioeconomically equitable manner.

- Secondary Considerations
    - Improved economies of sale
    - Improved project siting
    - Exploration of new models for service delivery and project financing.

A community scale approach to solar water heating in LA County is consonant with the considerations listed above. LA County has a mild, Mediterranean climate with abundant sunshine, but land use and development patterns range from densely populated urban areas to near-rural exurbs. In places where residents cannot afford to install separate domestic systems, or where space for system infrastructure is limited, a community scale approach offers opportunities for all participants to receive the benefits of solar water heating and support their system’s operation. Residents may contribute by allowing system infrastructure to be installed on their property, or by contributing financially if they do not own property on which collectors or tanks can be placed.

Studies of solar district heating in Northern Europe suggest that there are positive returns to scale for solar water heating systems. Figure 3 shows that both the cost per unit heat delivered and system cost per collector diminish as the total collector area of a district solar heating plant increases.

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[16] U.S. National Renewable Energy Lab. (2010). *A Guide to Community Solar: Utility, Private, and Non-profit Project Development.* Retrieved from: https://www.nrel.gov/docs/fy11osti/49930.pdf

[17] California Energy Commission. (2017). *Renewable Energy Secure Communities.* Retrieved from: http://www.energy.ca.gov/research/renewable/community.html

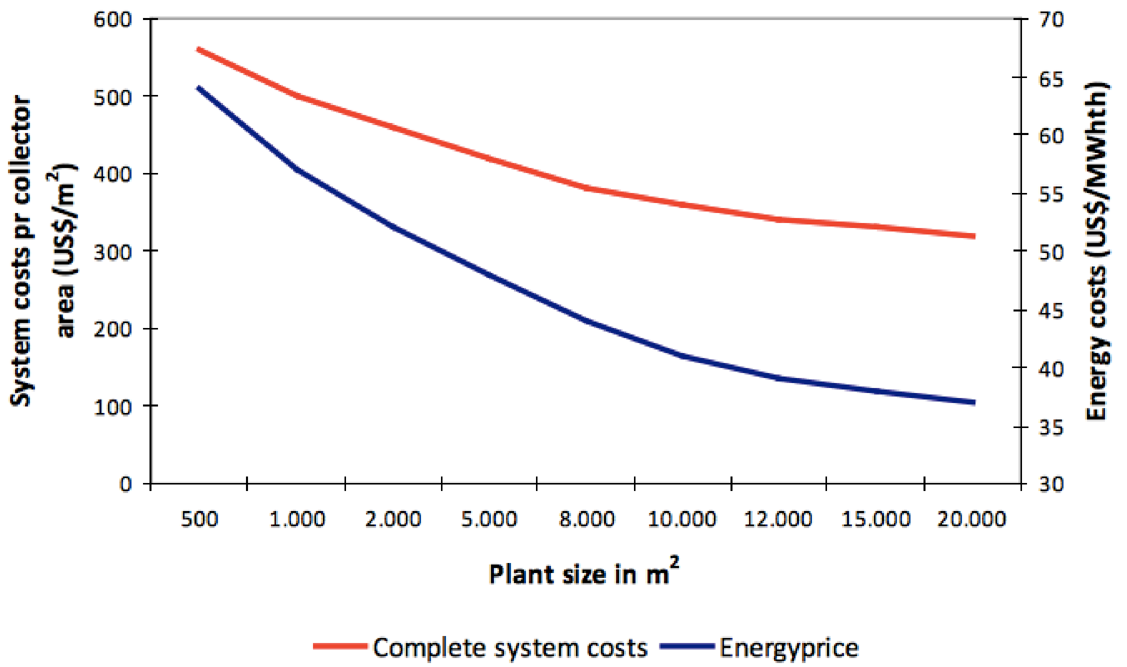

Figure 3: Energy cost and system cost per collector vs. collector area for district solar heating systems.[18]

A community scale approach to solar water heating may be superior in terms of economic efficiency to the installation of many smaller domestic solar water heating systems. The proportion of the heat load supplied by solar energy, called the *solar fraction* of a system, depends on the amount of useful heat collected and the thermal losses from various system components.[19] Larger systems require larger storage tanks, which store heat more efficiently than numerous smaller tanks, thus diminishing the cost per unit heat delivered.[20] Furthermore, community scale systems distribute fixed costs among many users, allowing residents who do not have the financial resources to install their own solar water heating systems to enjoy low carbon hot water and reduce their consumption of natural gas.[21]

[18] U.S. Army Corps of Engineers. (2011). *Central Solar Water Heating Systems Design Guide*. Retrieved from: http://www.solarthermalworld.org/sites/gstec/files/presentation%20Central%20Solar%20Hot%20Water%20Systems.pdf

[19] Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes*. John Wiley & Sons.

[20] *Ibid.*

[21] Del Chiaro, B. & Telleen-Lawton, T. (2007). *Solar Water Heating: How California Can Reduce Its Dependence on Natural Gas.* Environment California Research & Policy Center. Retrieved from: https://www.arb.ca.gov/cc/ccea/comments/jan/environment_california_swh.pdf

1.4 Benefits of Reduced Gas Consumption

Reducing residential natural gas consumption will in turn reduce greenhouse gas emissions, diminish concentrations of local air pollutants (such as SO_2 and NO_x), and mitigate the likelihood of major fires and natural gas leaks.

Given the share of natural gas deliveries consumed to heat water, the end use is an attractive target for reducing the greenhouse gas emissions from the residential housing sector. In 2016, California's residential gas consumption for water heating totaled 201,795 million cubic feet, resulting in the emission of eleven million tons of CO_2.[22] This volume of carbon dioxide is equal to that emitted annually by an American city with a population ~700,000.[23] Since water heating accounts for 25% of residential energy consumption, energy savings from an increased share of renewable heat are non-trivial.

Reducing residential natural gas consumption will also reduce the probability and severity of a catastrophic failure of LA County's gas delivery and storage infrastructure. Accidental releases of methane, both large and small, increase California's emissions budget and make achieving its climate goals more difficult. The 2015 Aliso Canyon Gas Leak alone released 5 billion cubic feet of methane in 112 days, equivalent to the annual emissions of ~600,000 cars.[24] The storage and transmission of methane leads inevitably to releases that increase California's emissions footprint.

In addition to the environmental costs of leakages, a large earthquake in Los Angeles County could ignite numerous gas-fueled fires. A study by the California Seismic Safety Commission estimated that 20-50% of fires resulting from a major earthquake ($M > 6.0$) will be caused by the ignition of natural gas leaks.[25] Reducing residential demand for natural gas will reduce the volume of gas that must be stored and delivered, mitigating the risk of leakages and fires.

Finally, reducing natural gas consumption will yield public health benefits. The combustion of natural gas produces fewer co-pollutants (such as sulfur or mercury) than the burning of other fossil fuels, but it is still a source of NO_x, CO, and other by-products

[22] U.S. Energy Information Administration. (2017). *California Natural Gas Consumption by End Use 1997-2016 [Data set]*. Retrieved from: https://www.eia.gov/dnav/ng/ng_cons_sum_dcu_SCA_a.htm

[23] European Commission Joint Research Centre - EDGAR. (2017). *CO2 time series 1991-2015 per capita for world countries [Data Set]*. Retrieved from: http://edgar.jrc.ec.europa.eu/overview.php?v=CO2ts_pc1990-2015

[24] Michanowicz, D. R., Buonocore, J. J., Rowland, S. T., Konschnik, K. E., Goho, S. A., & Bernstein, A. S. (2017). A national assessment of underground natural gas storage: identifying wells with designs likely vulnerable to a single-point-of-failure. *Environmental Research Letters, 12*(6), 64004. https://doi.org/10.1088/1748-9326/aa7030

[25] California Seismic Safety Commission. (2002). *Improving Natural Gas Safety in Earthquakes.* Retrieved from: http://www.seismic.ca.gov/pub/Final%20CSSCGasSafetyReport%20w%20Figures%207-15-02%20Version.pdf

linked to respiratory and cardiovascular illnesses.[26] Burning less natural gas will reduce local air pollution levels, improve public health, and reduce mortality.

Residential use of natural gas also carries with it the risk of carbon monoxide (CO) poisoning. Improperly ventilated or malfunctioning water or space heating devices can cause potentially lethal levels of . From 1999-2010, non-fire related CO fatalities occurred at a rate of 430 per year in the US.[27] Men and women over the age of 65 are most likely to die from CO poisoning (0.42 and 0.18 deaths per 100,000 people, respectively).[28]

1.5 Scope of This Report

This report reviews the relevant component technologies for solar water heating systems, the industry and building codes relevant to their siting and construction, and design principles for large-scale solar thermal systems. Review of these topics will allow for the specification of a basic solar water heating system design appropriate for residential water heating in LA County. The report will specify the following:

1. Solar Collector Technology Type & Thermal Efficiency
2. Energy Storage Time Horizon (i.e. Diurnal vs. Seasonal Storage)
3. Auxiliary or Back-up Heat Source Required
4. Methods for Predicting Solar Fraction and System Performance

This report will conclude with a basic description of the community scale solar water heating system design for the purposes of this analysis. The system design criteria will include LA County's climate, relevant state and municipal regulations, and cost. Establishment basic system characteristics is necessary prior to the estimation of energy savings in subsequent case studies. Other parameters that affect system performance, such as collector areas and system volumes, will be determined on a case-by-case basis, since available space for system infrastructure will differ between case study sites.

2 Solar Water Heating Components and Systems

The fundamental elements of solar water heating systems include solar thermal collectors, storage tanks (to store the heated working fluid/ heated water), and piping systems to move heated water and working fluid between collectors, storage tanks, and buildings. Additional elements may include heat exchangers, auxiliary gas heaters, buffer tanks, and seasonal heat storage systems. Control mechanisms for solar water heating

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[26] Haines, A., McMichael, A. J., Smith, K. R., Roberts, I., Woodcock, J., Markandya, A., … Wilkinson, P. (2009). Health and Climate Change 6 Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *The Lancet*, *374*, 2104–2114. https://doi.org/10.1016/S0140

[27]Centers for Disease Control and Prevention. (2014). *QuickStats: Average Annual Number of Deaths and Death Rates from Unintentional, Non-fire Related Carbon Monoxide Poisoning by Sex and Age Group – United States, 1999-2010.* Retrieved from: https://www.cdc.gov/mmwr/preview/mmwrhtml/mm6303a6.htm

[28] *Ibid.*

systems depend on a given system's size and complexity.[29] The sections below discuss the purposes and working principles of solar water heating systems' component parts.

2.1 Solar Thermal Collectors

Solar thermal collectors absorb thermal energy from incident solar radiation, and transfer to water or a working fluid. The four most common collector types are:

- Flat Plate Collectors (FPCs)
- Evacuated Tube Collectors (ETCs)
- Integral Collector-Storage Systems (ICSS)
- Integrated Photovoltaic/ Thermal (PV/T) Collectors

Selection of a collector type depends on the desired application and cost. The amount of useful heat a collector delivers to a given system is a function of the amount of incident solar radiation, the difference between ambient temperature and that of the unit, and the temperature of the heat transfer fluid at the collector inlet.[30] Collector performance is also affected by the angle of insulation and local meteorological conditions.[31] Table 1 lists the peak thermal efficiencies for different collector types measured in laboratory settings.

Table 2: Thermal Efficiency Ranges of Solar Collector Technologies – Peak thermal efficiencies show here are based on laboratory studies measuring useful heat output obtained from a fixed amount of incident radiation and an ambient temperature equal to collector inlet temperature ($T_i = T_a$).

Collector Type	Peak Thermal Efficiency (T_i=T_a)
Flat Plate	70-80%[32, 33]
Evacuated Tube	~60%[34]
PV/T	50-70%[35]

[29] Fisch, M. N., Guigas, M., & Dalenbäck, J.-O. (1998). A review of large-scale solar heating systems in Europe. *Solar Energy*, *63*(6), 355–366. https://doi.org/10.1016/S0038-092X(98)00103-0

[30] Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes*. John Wiley & Sons.

[31] *Ibid.*

[32] Zondag, H. A. (2008). Flat-plate PV-Thermal collectors and systems: A review. *Renewable and Sustainable Energy Reviews*. https://doi.org/10.1016/j.rser.2005.12.012

[33] Ayompe, L. M., Duffy, A., Mc Keever, M., Conlon, M., & Mccormack, S. J. (2011). Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. https://doi.org/10.1016/j.energy.2011.03.034

[34] *Ibid.*

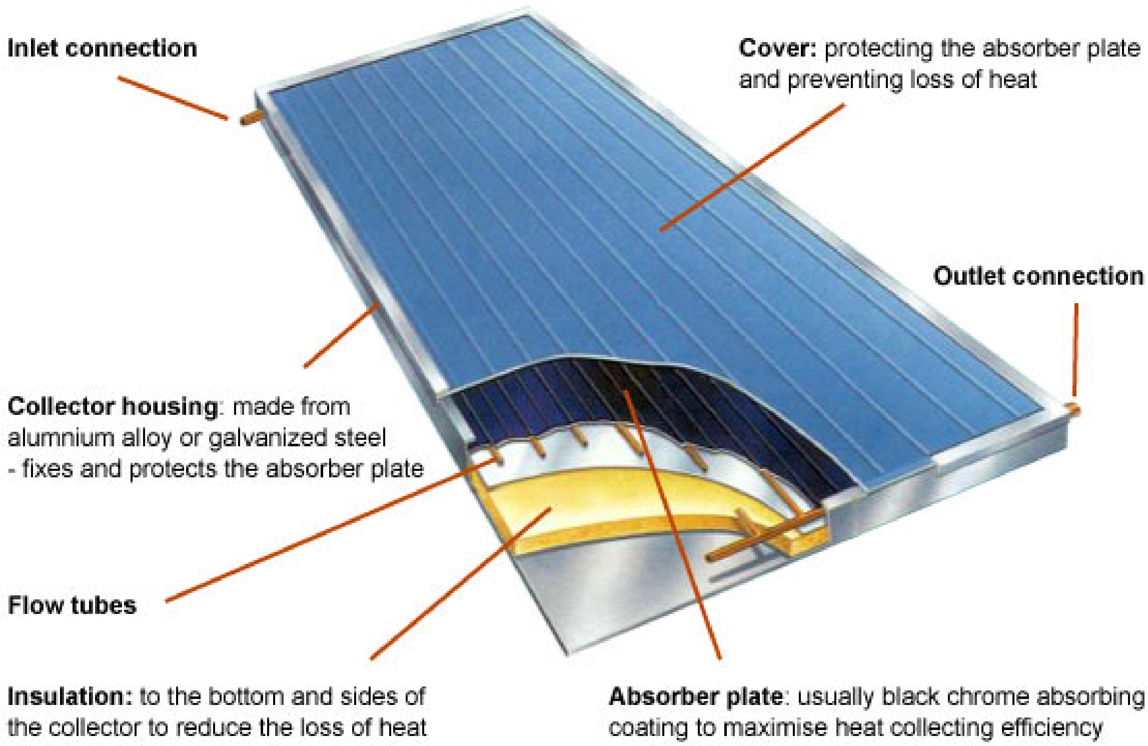
[35] Dubey, S., & Tiwari, G. N. (2008). Thermal modeling of a combined system of photovoltaic thermal (PV/T) solar water heater. *Solar Energy*. https://doi.org/10.1016/j.solener.2008.02.005

Integrated Collector Storage	Variable[36]

Flat Plate Collectors (FPCs)

A flat plate collector is an insulated box containing an absorber plate and a network of flow tubes covered by a sheet of translucent glass or plastic. Most FPCs have copper flow tubes and absorber plates with selective coatings to reduce reflection. [37]

FPCs transfer heat to water or a working fluid as it passes through the network of flow tubes in thermal contact with the absorber plate. The translucent cover serves to reduce heat losses from convection. Figure 2 shows a typical FPC design.



[36] Smyth, M., Eames, P. C., & Norton, B. (2006). Integrated collector storage solar water heaters. *Renewable and Sustainable Energy Reviews*, *10*(6), 503–538. https://doi.org/10.1016/j.rser.2004.11.001

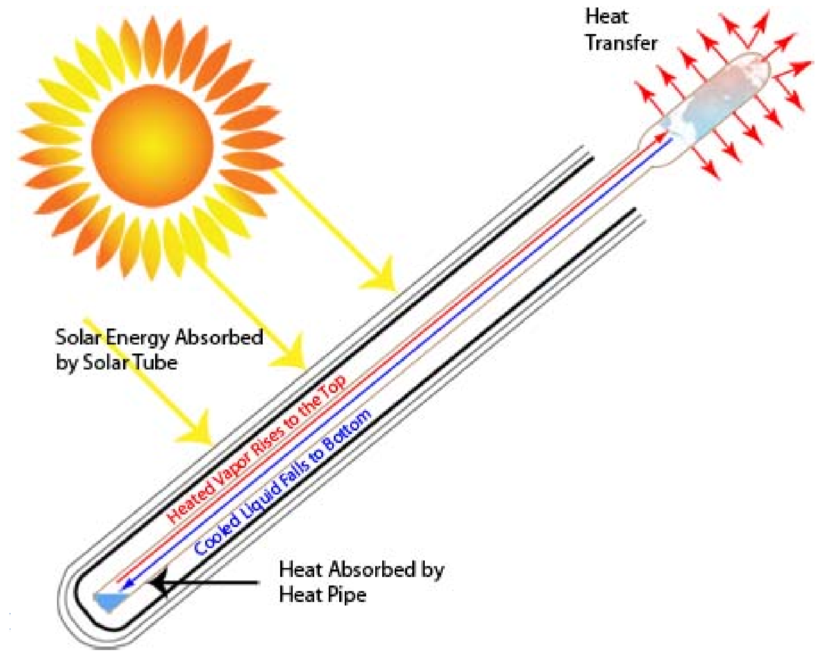
[37] Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes*. John Wiley & Sons.

[38] https://www.designingbuildings.co.uk

Stud results in a thermal efficiency of approximately 75%[39] This should be considered an upper limit on the thermal efficiency of a flat plate collector, as their thermal efficiencies are sensitive to changes in ambient temperature.[40,41] The Drake's Landing, in Northern coastal California, solar community project, which uses and array of 800 flat plate panels to provide space and water heating, has documented a thermal efficiency range for the collection system (collectors and pipes) between 30-70%, with an average of approximately 50%.[42]

Evacuated Tube Collectors

Evacuated tube collectors consist of an array of evacuated glass tubes, each containing a smaller glass tube within. The inner glass tube houses an absorber plate in thermal contact with a flow tube. A vacuum between the two glass layers serves to thermally insulate the inner tube.



[39] Zambolin, E., & Del Col, D. (2010). Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions. *Solar Energy*, *84*(8), 1382-1396.
[40] *Ibid.*
[41] *Ibid.*
[42] Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., & Kokko, J. (2012). The performance of a high solar fraction seasonal storage district heating system - Five years of operation. *Energy Procedia*, *30*, 856–865. https://doi.org/10.1016/j.egypro.2012.11.097

There are two main types of evacuated tube collector designs, but all designs employ absorptive coatings on the surface of either the inner tube wall or the absorber plate. Some evacuated tube collector designs include heat pipes that terminate in heat bulbs, around which water flows through a heat exchange manifold. Alternatively, direct circulation designs circulate a working fluid through u-shaped pipes within each of the inner tubes, and return the heated fluid to a header pipe.

A comparative study of flat plate and direct circulation evacuated tube collectors' thermal efficiencies found that evacuated tube collectors have slightly lower peak thermal efficiencies than flat plate collectors (<60%), but are less sensitive to changes in ambient temperature and the direction of incident solar radiation.[43] Evacuated tube collectors are more efficient over a greater range of meteorological conditions and temperatures than flat plate designs.[44] The superior thermal performance of ETCs in variable weather conditions is also supported by data from a study domestic solar water heating systems in Dublin, Ireland.[45] ETC systems had greater average annual solar fractions (50.3%) than FPC systems (37.9%).[46]

Integral Collector Storage System (ICSS)

Integral collector storage systems are the oldest and simplest type of solar thermal collector technology.[47] Integral collector storage systems store heated water within the solar thermal collection device, rather than in a separate tank (i.e. a distributed system).[48] A wide variety of designs for integral collector storage systems exist. Integral collector storage systems may employ a flat plate design with storage tanks instead of flow tubes, use a series of evacuated tubes that terminate in a storage tank, or employ reflectors and phase-change materials to maximize heat absorption and minimize thermal losses.[49]

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[43] Zambolin, E., & Del Col, D. (2010). Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions. *Solar Energy*, *84*(8), 1382–1396. https://doi.org/10.1016/j.solener.2010.04.020
[44] *Ibid.*
[45] Ayompe, L. M., Duffy, A., Mc Keever, M., Conlon, M., & McCormack, S. J. (2011). Comparative field performance study of flat plate and heat pipe evacuated tube collectors (ETCs) for domestic water heating systems in a temperate climate. Energy, 36(5), 3370-3378.
[46] *Ibid.*
[47] Smyth, M., Eames, P. C., & Norton, B. (2006). Integrated collector storage solar water heaters. *Renewable and Sustainable Energy Reviews*, *10*(6), 503-538.
[48] *Ibid.*
[49] *Ibid.*

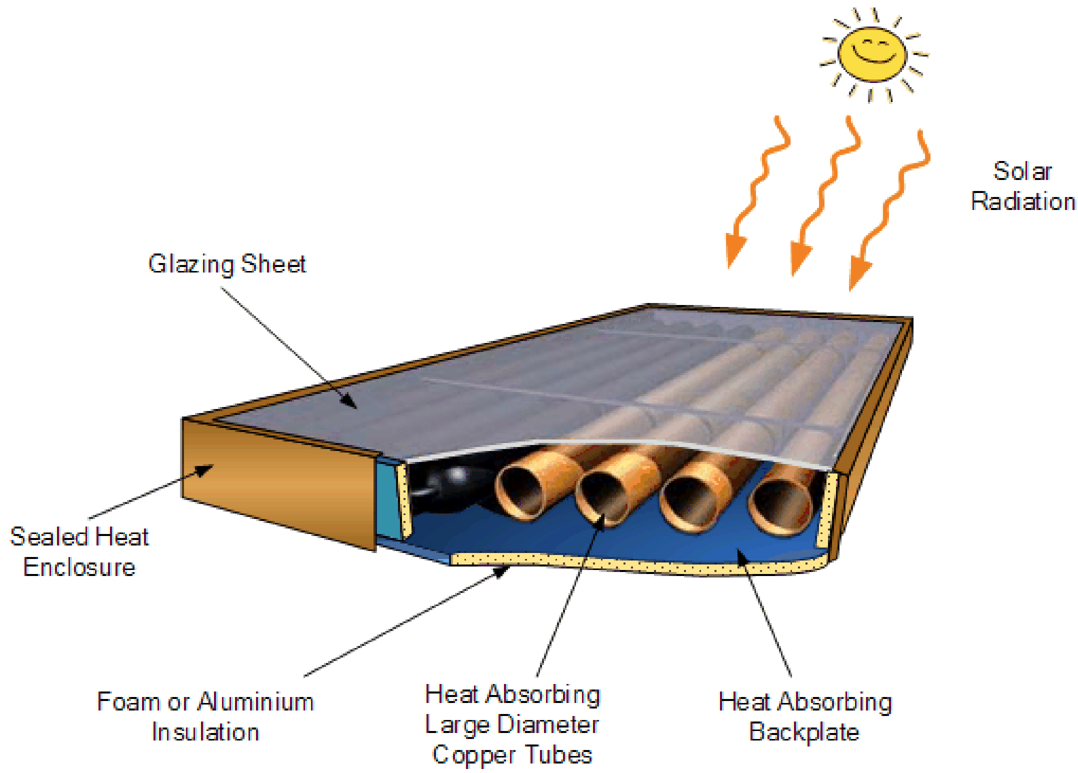

Figure 6: Integrated Solar Collector Storage System[50]

Integral collector storage systems generally suffer greater thermal losses during nighttime and non-operative periods than distributed systems.[51] Distributed systems feature physically separate storage and collector equipment to minimize thermal losses and improve storage efficiency. Thermal efficiencies vary widely based on the specific collector/storage design used in a given implementation. ICSSs are most often used to pre-heat potable water for a single residence.[52] Pre-heated water is then brought up to the desired delivery temperature with a conventional gas or electric water heater.

Integrated PV/T Collectors

Integrated PV/T collectors couple the generation of electric current from photovoltaic solar cells with the collection thermal energy for water and space heating. The conversion of solar energy into electric current via the photoelectric effect is a process which is a relatively inefficient process that produces a large amount of waste heat. The collection of waste heat from PV cell arrays both increases the efficiency of the cells themselves

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50 http://www.alternative-energy-tutorials.com/images/stories/heating/alt39.gif

51 *Ibid.*

52 Smyth, M., Eames, P. C., & Norton, B. (2006). Integrated collector storage solar water heaters. Renewable and Sustainable Energy Reviews, 10(6), 503-538.

(which diminishes as their temperature increases) and provides thermal energy for space and water heating.[53]

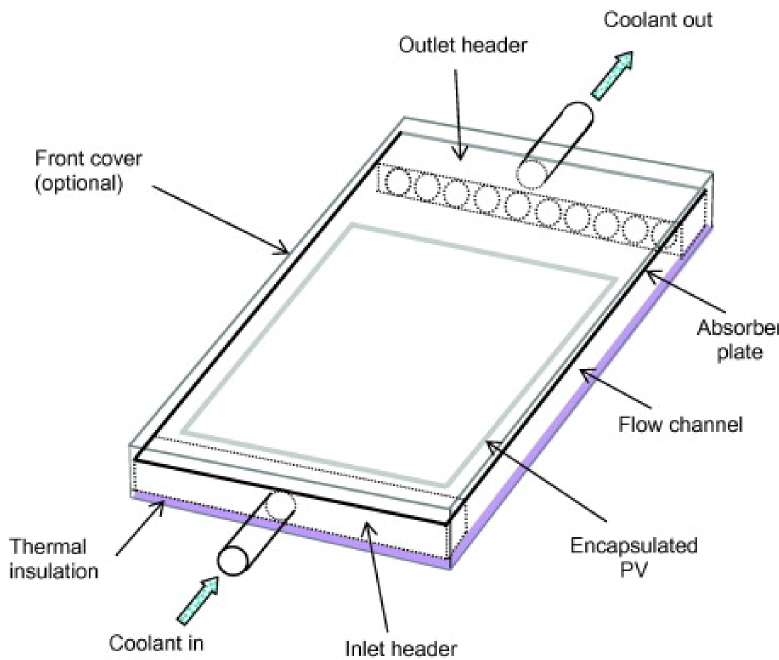

Figure 7: PV/T Cell[54]

A myriad of PV/T collector designs exist, but all systems involve the circulation a fluid coolant to collect waste heat from photovoltaic cells. PV/T collectors may include a translucent housing or cover to increase thermal absorptivity.[55] Theoretically, PV/T technology is be the most efficient method for collecting solar energy. High-performing PV/T cells could potentially obviate the need for separate photovoltaic and thermal systems. However, the lower thermal performance of PV/T systems relative to other solar thermal collectors has limited PV/T's adoption.[56] PV/T systems collect solar thermal energy indirectly, only about 75% of incident solar energy is available in the form of

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53 Huang, B. J., Lin, T. H., Hung, W. C., & Sun, F. S. (2001). Performance evaluation of solar photovoltaic/thermal systems. *Solar Energy*, *70*(5), 443–448. https://doi.org/10.1016/S0038-092X(00)00153-5

54 Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. *Applied Energy*, *87*(2), 365–379. https://doi.org/10.1016/j.apenergy.2009.06.037

55 *Ibid.*

56 Dupeyrat, P., Menezo, C., & Fortuin, S. (2014). Study of the thermal and electrical performances of PVT solar hot water system. *Energy and Buildings*, *68*(PART C), 751–755. https://doi.org/10.1016/j.enbuild.2012.09.032

heat. Maximum thermal efficiencies for PV/T solar collectors range from 50-70%.[57, 58] Like the other collector technologies discussed previously, thermal efficiencies of PV/T collectors vary depending on ambient temperature, meteorological conditions, and the angle of incident radiation.[59]

The largest PVT system installed in the US serves the Schofield Barracks, a US Army base on Oahu. The system collects thermal energy through hydronic thermal collection frames placed on 40% of the roof mounted PV cells.[60] The system is able to capture approximately 75% of the waste heat from the generation of electrical current.[61]

2.2 Storage Tanks

The design and use of storage tanks for water and working fluid has a significant impact on the thermal performance of solar water heating systems.[62] Storage tank insulation and temperature stratification help to minimize thermal losses from solar hot water heating systems. Thermal insulation of tanks helps minimize losses to the ground and air, especially during colder months. Many domestic and community-scale solar water heating systems take advantage of temperature stratification in their designs to increase thermal efficiency.[63, 64, 65]

Thermal stratification refers to the tendency of hotter, less dense, water to rise to the top of a column. Thermally stratified tanks are designed so as to preserve a temperature gradient along the axis of a storage tank. Hot water may be discharged for consumption from the hottest part of the tank, while water from the coldest part of the tank may be recirculated though the collector array or heat exchanger. Modeling and physical studies of solar hot water heating systems have found that systems employing stratified tanks can

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[57] Chow, T. T. (2010). A review on photovoltaic/thermal hybrid solar technology. *Applied Energy*, *87*(2), 365–379. https://doi.org/10.1016/j.apenergy.2009.06.037
[58] Dupeyrat, P., Menezo, C., & Fortuin, S. (2014). Study of the thermal and electrical performances of PVT solar hot water system. *Energy and Buildings*, *68*(PART C), 751–755. https://doi.org/10.1016/j.enbuild.2012.09.032
[59] *Ibid.*
[60] Schroeder, J. (2013). *Hybrid PVT System Successful in Oahu.* AGWIRED. Retrieved from: http://energy.agwired.com/2013/07/10/hybrid-pvt-solar-system-successful-in-oahu/
[61] *Ibid.*
[62] Cruickshank, C. A., & Harrison, S. J. (2010). Heat loss characteristics for a typical solar domestic hot water storage. *Energy and Buildings*, *42*(10), 1703–1710. https://doi.org/10.1016/j.enbuild.2010.04.013
[63] *Ibid.*
[64] Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W., & Müller-Steinhagen, H. (2010). German central solar heating plants with seasonal heat storage. *Solar Energy*, *84*(4), 612–623. https://doi.org/10.1016/j.solener.2009.05.013
[65] Hollands, K. G. T., & Lightstone, M. F. (1989). A review of low-flow, stratified-tank solar water heating systems. *Solar Energy*, *43*(2), 97–105. https://doi.org/10.1016/0038-092X(89)90151-5

deliver approximately 30% more energy than systems that maintain a uniform tank temperature.[66]

Auxiliary and Backup Heating Elements
Due to economic and practical considerations, most solar water heating systems are not designed to meet 100% of their heat loads with solar energy.[67] Instead, systems are designed to provide hot water at a minimum solar fraction, and use an in-line auxiliary heater to ensure adequate delivery temperature. Auxiliary heaters may also be integrated in to storage tanks, rather than placed in-line with the storage tank outlet pipe. At domestic scales, tank-less water heating units have sufficient power to satisfy demand in the event of insufficient solar radiation or system malfunction.

For systems larger than domestic scale, it may be necessary to include back-up heating units to ensure that hot water can by supplied in the event of inclement weather or malfunction.[68] A range of options for back-up heaters exists, including heat pumps, electric and gas heaters, and biomass boilers.[69] Choice of a particular backup technology is depends on application and cost.

Heat Exchange Fluids and Heat Exchangers
Closed systems with freeze resistant heat exchange fluids are required in climates that experience prolonged freezing temperatures, as most collectors are not designed to withstand such forces. Antifreeze agents are also toxic, requiring a heat exchanger be installed between the collection and storage/ delivery loops.

Common heat exchange fluids include glycol/ water mixtures, hydrocarbon oils, and silicones. Choice of a heat transfer fluid depends on system design and meteorological conditions.[70]

2.3 System Types

Passive vs. Active Systems
The terms “passive” and “active” describe whether a solar heating system uses energy to circulate water or working fluid through the collector array. Active systems use pumps and powered control elements to circulate water or a working fluid. There are two basic active system designs: direct systems, which circulate water through solar thermal collectors, and closed systems, which use a working fluid and heat exchangers to transfer energy to stored water.[71]

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[66] *Ibid.*
[67] Duffie, J. A., & Beckman, W. A. (2013). *Solar engineering of thermal processes*. John Wiley & Sons.
[68] *Ibid.*
[69] U.S. Army Corps of Engineers. (2011). *Central Solar Hot Water Systems Design Guide.* Retrieved from: https://www.wbdg.org/FFC/ARMYCOE/COEDG/dg_solar_hot_water.pdf
[70] U.S. Department of Energy. (2017). *Heat Transfer Fluids for Solar Water Heating Systems*. Retrieved from: https://energy.gov/energysaver/heat-transfer-fluids-solar-water-heating-systems
[71] *Ibid.*

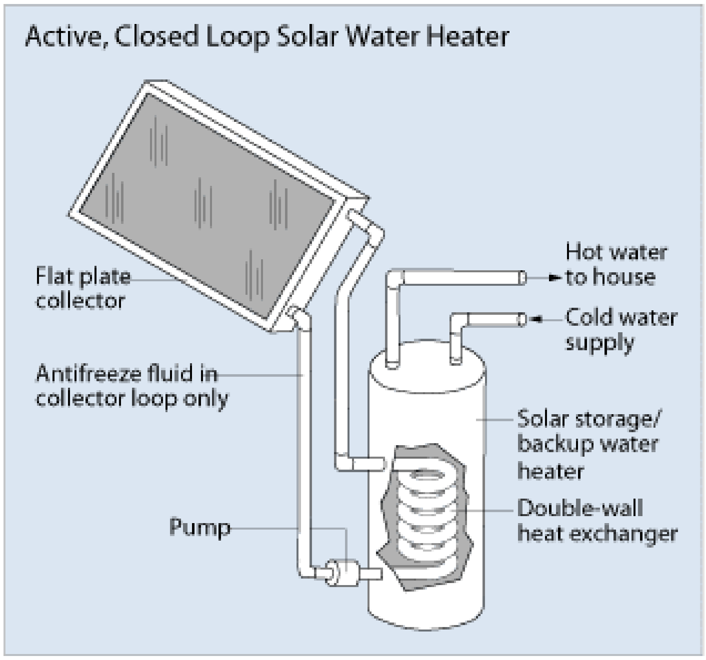
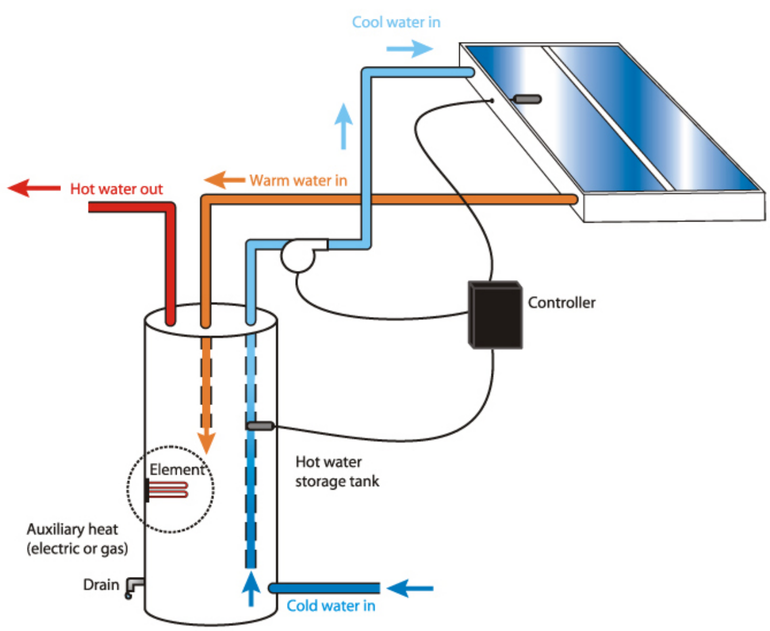


Figure 8: Schematic of an active closed system[72]



Figur

[72] Source: https://energy.gov/energysaver/solar-water-heaters
[73] http://www.acmegreen.com/page2/page7/files/page7_1.jpg

Passive systems do not use energy to circulate water through collector arrays. The two most common types of passive systems are thermosiphon and integral collector storage systems. Thermosiphon systems rely on convection to circulate water. The collection of solar thermal energy creates a temperature gradient within the system, resulting in a difference in density, and thus a buoyancy force. As heated water moves from the collector array into a storage tank, it is replaced by cold water at the bottom of the array. Circulation occurs so long as a temperature (and thus a density) gradient is maintained within the system.[74] Storage tanks must be elevated relative to collector arrays for a thermosiphon system to function properly. If not, heat lost by the system through the collector array will reverse the direction of flow, cooling the water held in the storage tank.[75]

Integral collector storage systems transfer solar thermal energy to a fixed volume of water, which is then discharged to a storage tank or backup water heater. Backup heaters may be used to maintain or boost water temperatures prior to delivery of hot water.[76] Most ISCSSs require pumps to circulate fluid through the collector array and deliver hot water to end users.

2.4 System Scale

SWH systems range in scale from domestic, single-residence systems to district-scale systems with thousands of cubic meters of collector area. System scale is among the most important design considerations, influencing choice of component technologies, collector area, and storage capacity.

Domestic

Domestic scale systems are designed to provide heat to a single residential unit or structure. This scale encompasses the widest variety of system designs.

Most domestic scale systems are not designed to supply 100% of the thermal energy needed for hot water, but to offset the use of gas or electricity for water heating. Systems are designed to pre-heat water which is then boosted by an auxiliary heater to reach delivery temperature.

Passive systems (thermosiphon and integral collector storage systems) are most common at the domestic scale. To function properly, passive systems must have collector arrays located below the storage tank, and the storage tank must be installed above the fixtures where hot water is to be used. While passive system designs are potentially sufficient for single residences, they are not practical for larger scales.

Multi-Family

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[74] Kalogirou, S. (2009). Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. *Solar Energy*, *83*(1), 39–48. https://doi.org/10.1016/j.solener.2008.06.005
[75] *Ibid.*
[76] *Ibid.*

Multi-family SWH systems are designed to meet the needs of multiple residences, most often within a single structure. Multi-family SWH systems use the same component technologies as domestic systems, but require larger storage tanks and collector areas to meet the heat loads of multiple residences. Most multi-family SWH systems are also active.

Systems at this scale typically take advantage of a centralized design for hot water storage and distribution. Collector arrays transfer thermal energy to a large central storage tank from which hot water is delivered. Centralized storage improves the thermal performance of a SWH system by reducing surface area to volume ratio, thus diminishing heat loss through the walls of the storage tank.

For the purposes of this report and analysis, community scale SWH systems will adhere to the relevant requirements building code and energy efficiency requirements for multi-family buildings. Community scale systems, even if they serve single residences, may be thought of as de facto multi-family systems.

District

District scale solar thermal systems are designed serve hundreds to thousands of residential units, and differ substantially from smaller scale systems. District scale solar thermal systems are often integrated into existing central heating networks to provide additional, renewable thermal energy. Other district scale systems are designed to provide space and water heating at high solar fractions, and minimize the use of other sources of energy. Most district scale systems have been constructed in Northern latitudes where heating loads are higher, and space heating represents a greater fraction of residential energy use.

Extant systems fall into two categories: Diurnal and seasonal. Diurnal systems are designed provide 10-20% of annual heat loads, and have no long-term heat storage apparatus.[77] Seasonal systems have large, long-term heat storage components, and are designed to provide >50% of annual heat loads.[78] Studies of seasonal systems in Northern Europe and Canada document a range of solar fractions between 40-90%, depending on the details of system design.[79, 80]

[77] Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2004). Central solar heating plants with seasonal storage in Germany. *Solar Energy*, *76*(1–3), 165–174. https://doi.org/10.1016/j.solener.2003.07.025
[78] *Ibid.*
[79] Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W., & Müller-Steinhagen, H. (2010). German central solar heating plants with seasonal heat storage. *Solar Energy*, *84*(4), 612–623. https://doi.org/10.1016/j.solener.2009.05.013
[80] Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., & Kokko, J. (2012). The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation. *Energy Procedia*, *30*, 856–865. https://doi.org/10.1016/j.egypro.2012.11.097

The greatest difference between district scale solar thermal systems and others is that district scale systems often need to store heat to meet greater demand and heat loads during winter months when less thermal energy is available. Excess thermal energy collected during summer months is stored and discharged when collectors cannot supply sufficient heat to meet delivery temperatures.[81]

Large Scale/ Seasonal Heat Storage Technologies

All district scale seasonal systems constructed to date use sensible heat storage technologies. [82] Sensible systems store heat by transferring energy to a thermally insulated storage medium, such as a volume of water, a parcel of earth, or an aquifer. Selection of the appropriate heat storage technology depends on geological and meteorological factors, such as seismicity, groundwater flows, seasonal variation in ambient temperature, and desired solar fraction of the system.

Hot Water Storage

Many of the district- scale solar hot water heating systems constructed to date simply heat and store large volumes of hot water in well-insulated tanks to meet hot water demand. Storage tanks may be installed above or below-ground. Tanks are insulated with a range of materials, such as glass wool or polyurethane.[83] Hot water storage tanks are also typically lined to prevent corrosion and provide an additional layer of insulation. Below is a schematic of a community-scale system with hot water storage constructed in Freidrichshafen, Germany.

[81] Fisch, M. N., Guigas, M., & Dalenbäck, J.-O. (1998). A review of large-scale solar heating systems in Europe. *Solar Energy*, *63*(6), 355–366. https://doi.org/10.1016/S0038-092X(98)00103-0
[82] Xu, J., Wang, R. Z., & Li, Y. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, *103,* 610–638. https://doi.org/10.1016/j.solener.2013.06.006
[83] *Ibid.*

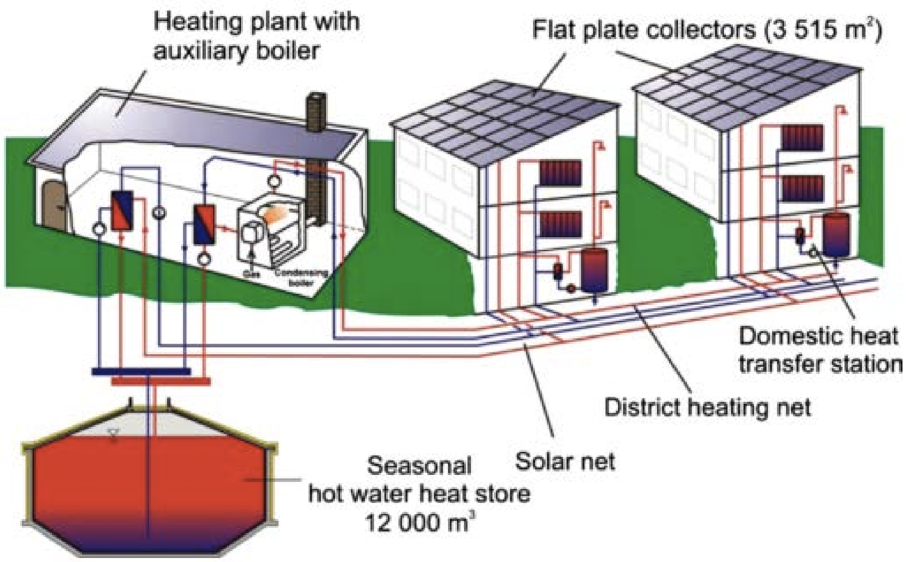

Figure 10: Hot water seasonal heat storage for a district heating network[84]

Hot water storage tanks are designed to leverage naturally occurring temperature gradients (thermal stratification) to increase system efficiency. Hot water from the top of the tank may be pumped into buffer tanks, auxiliary heaters or directly into the delivery circuit of the hot water system to meet demand, while cooler water drawn from the bottom of the tank may be sent to the collection circuit to absorb additional heat.

Seasonal hot water storage tanks are simple, scalable, and relatively inexpensive to build. High heat capacities and charging and discharging rates makes them an attractive option, given their small footprint. However, systems built around them typically achieve relatively low solar fractions. Existing systems have achieved solar fractions between 16-49%.[85] Studies of two German seasonal hot water storage systems found that lower than expected solar fractions were due in part to high return temperatures disturbing thermal stratification within the storage tank.

Water/ Gravel Storage

Volumes of water mixed gravel have also been used as seasonal stores of thermal energy. While the heat capacity of pure water is great than that of a gravel/ water mixture, this method of heat storage has the lowest capital cost relative to the other seasonal heat storage methods, as there is no need for a special insulated structure.[86]

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[84] Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W., & Müller-Steinhagen, H. (2010). German central solar heating plants with seasonal heat storage. *Solar Energy*, *84*(4), 612–623. https://doi.org/10.1016/j.solener.2009.05.013

[85] Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2004). Central solar heating plants with seasonal storage in Germany. Solar Energy, 76(1–3), 165–174.

[86] Pfeil, M., Koch, H. (2000). High performance-low cost seasonal gravel/water storage pit. *Solar Energy*, 69(6), 461-467. https://doi.org/10.1016/S0038-092X(00)00123-7

Water/ gravel seasonal heat stores consist of a conical pit lined with watertight plastic and insulating material into which layers of a water-gravel mixture are poured around a heat exchange coil.[87] The figure below depicts a typical design:

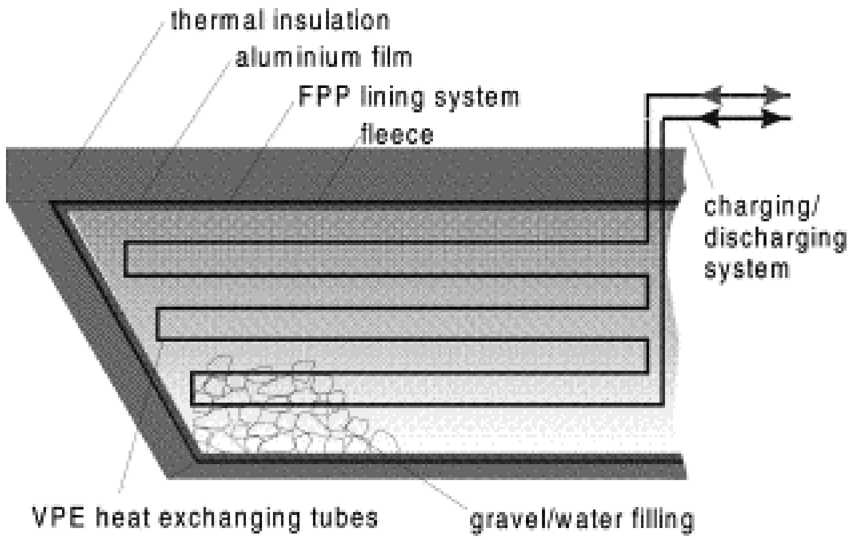

Figure 11: Water/ gravel pit sensible heat storage[88]

Solar fractions of community-scale water heating systems with water/gravel heat storage are comparable to those attained by systems with seasonal hot water storage tanks. The first solar heating system to use a water/gravel system achieved a solar fraction of 34%.[89]

Water/gravel heat store designs have some drawbacks. Because of the water/gravel mixture's low specific heat capacity, this method of heat storage often entails a large construction footprint. Water/gravel systems must have volumes approximately 50% greater than hot water storage tanks to achieve equal heat capacity.[90] Despite their low cost and simplicity, water/gravel systems may not be suitable for urban solar heating systems where space is limited.

Borehole Thermal Energy Storage (BTES)

Borehole thermal energy storage (BTES) is a recent and promising seasonal heat storage technology. BTES consist of a series of precisely spaced boreholes into which a network of U-shaped heat exchange tubes is inserted. The empty space within the boreholes is filled in with thermally conductive grout. The soil and earth between the boreholes becomes the heat storage medium, and heated water pumped into the BTES acts as the

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[87] Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2004). Central solar heating plants with seasonal storage in Germany. *Solar Energy*, *76*(1–3), 165–174. https://doi.org/10.1016/j.solener.2003.07.025
[88] Pfeil, M., & Koch, H. (2000). High performance–low cost seasonal gravel/water storage pit. Solar Energy, 69(6), 461–467. https://doi.org/10.1016/S0038-092X(00)00123-7
[89] *Ibid.*
[90] Xu, J., Wang, R. Z., & Li, Y. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, *103*, 610–638. https://doi.org/10.1016/j.solener.2013.06.006

transfer fluid.[91] The figure below illustrates a BTES design from a solar water heating system in Okotoks, Alberta, Canada.

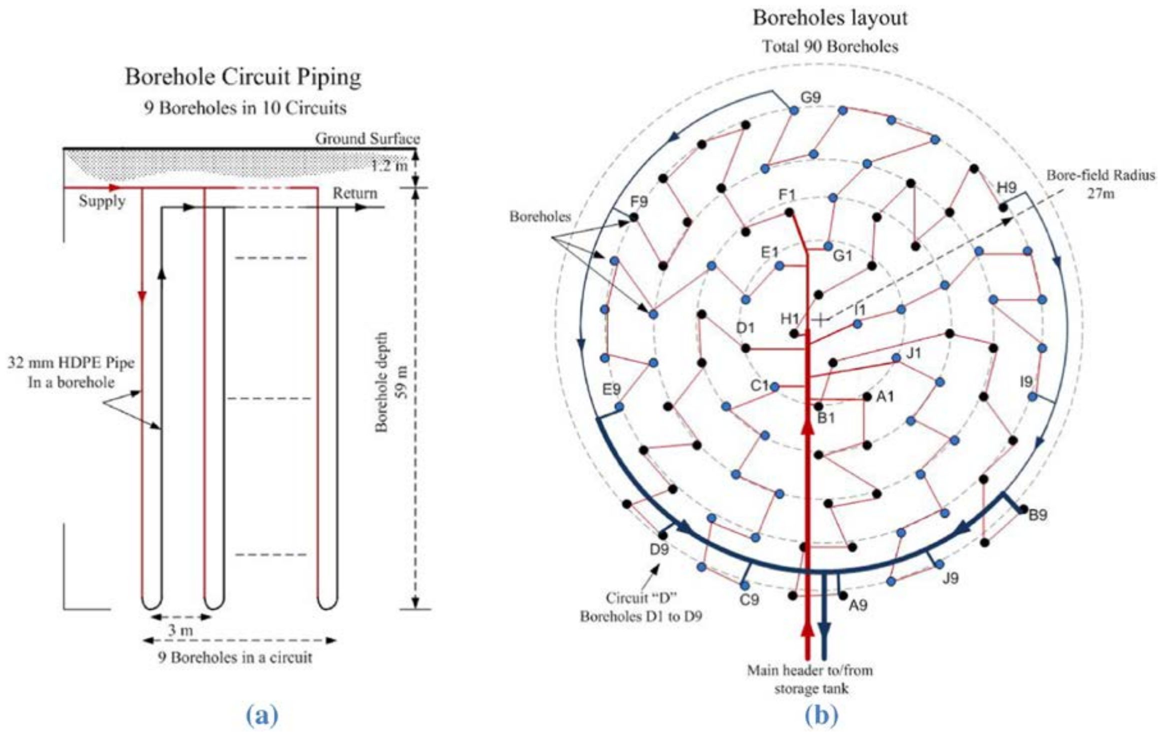


Figure 12: Borehole seasonal heat storage[92]

Recently constructed solar water heating systems with BTES can achieve very high solar fractions. The Drake's Landing Solar Community, which uses a BTES for seasonal energy storage (pictured above) maintained a solar fraction >50% during five years of operation, reaching a peak efficiency of 97% during the 5th year of a 5-year performance study.[93]

Solar heating systems with BTES are expensive, and require more complex control schemes than other types of seasonal hot water storage. BTES systems also require a charging period prior to achieving their desired operating solar fraction. During the charging period, hot water from the collector array is pumped into the center of the BTES, gradually raising the temperature of the ground between the boreholes. The fraction of heat supplied from the BTES increases as the storage system reaches

[91] *Ibid.*
[92] Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., & Kokko, J. (2012). The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation. *Energy Procedia*, *30*, 856–865. https://doi.org/10.1016/j.egypro.2012.11.097
[93] Sibbitt, B., McClenahan, D., Djebbar, R., Thornton, J., Wong, B., Carriere, J., & Kokko, J. (2012). The Performance of a High Solar Fraction Seasonal Storage District Heating System – Five Years of Operation. *Energy Procedia*, *30*, 856–865. https://doi.org/10.1016/j.egypro.2012.11.097

operating temperature. Depending on the duration and intensity of solar radiation, the process of fully charging a BTES can take a several years.[94]

Aquifer Thermal Energy Storage

Aquifer thermal energy storage (ATES) uses a natural aquifer to store collected solar thermal energy. If favorable geological conditions exist, ATES is potentially cost-effective option for seasonal heat storage. Several ATES systems in Germany and China demonstrate the design's potential to reach high solar fractions with acceptable heat losses.[95]

An ATES consists of hot and cold wells drilled into a natural aquifer. Water from the cold well is pumped into the collector array, heated, and then injected into the hot well of the aquifer for storage.[96] Whether ATES is an option for seasonal heat storage depends on local geological conditions. The earth surrounding the aquifer must be porous enough to allow the system to be charged and discharged at reasonable flow rates, but not so porous as to lead to excessive heat loss to the surroundings. Evaluation of local geological conditions is necessary to determine if an ATES is a feasible for a given application.[97]

[94] *Ibid.*
[95] Xu, J., Wang, R. Z., & Li, Y. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, *103*, 610–638. https://doi.org/10.1016/j.solener.2013.06.006
[96] Seibt, P., & Kabus, F. (n.d.). Aquifer Thermal Energy Storage – Projects Implemented in Germany. Retrieved from http://talon.stockton.edu/eyos/energy_studies/content/docs/FINAL_PAPERS/4A-1.pdf
[97] *Ibid.*

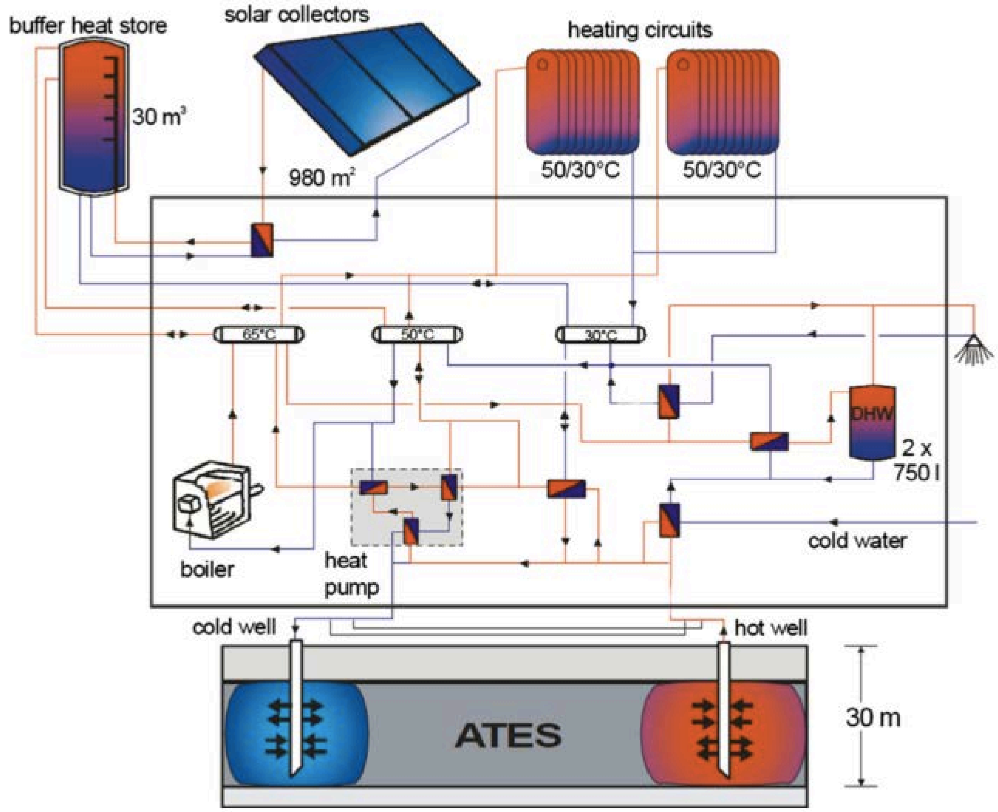


Figure 13: Aquifer thermal energy storage[98]

Solar hot water heating systems with ATES can achieve solar fractions of ~40-70%.[99, 100] Selection of an ATES for seasonal heat storage is entirely dependent on the existence of appropriate geological conditions.

2.5 Definition of Community Scale

Community scale SWH systems occupy a space between multi-family and district scale systems, combining characteristics from each. Community scale systems can be thought of as small hot water utilities, serving hundreds to thousands of residences. These systems are designed to leverage economies of scale by distributing fixed costs over a greater number of users, making optimal use of space for system infrastructure, and maximizing thermal efficiency with centralized storage of hot water. By virtue of the fact

[98] Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2004). Central solar heating plants with seasonal storage in Germany. *Solar Energy*, *76*(1–3), 165–174. https://doi.org/10.1016/j.solener.2003.07.025

[99] Xu, J., Wang, R. Z., & Li, Y. (2014). A review of available technologies for seasonal thermal energy storage. *Solar Energy*, *103*, 610–638. https://doi.org/10.1016/j.solener.2013.06.006

[100] Bauer, D., Marx, R., Nußbicker-Lux, J., Ochs, F., Heidemann, W., & Müller-Steinhagen, H. (2010). German central solar heating plants with seasonal heat storage. *Solar Energy*, *84*(4), 612–623. https://doi.org/10.1016/j.solener.2009.05.013

that community scale systems serve many residential unit, and are distributed across multiple residential properties, multi-family energy and building code requirements are most relevant to their siting and construction.

Community scale SWH systems are most like district scale systems with respect to size, but differ in several important respects. Community scale solar thermal systems considered here do not provide energy for space heating, given LA County's mild climate and relatively small residential space heating requirements. In colder climates, the cost and energy intensity of space heating often justifies the construction of a systems that provides both.

3 Review of Building and Industry Codes

The following section reviews the building and industry codes relevant to the design and construction of community scale SWH systems. First, standards for SWH system performance and component technologies are reviewed. These standards set minimum requirements for thermal performance and durability, influencing system design and cost. Secondly, because subsequent analyses will model the performance of community-scale SWH systems, special attention is paid to regulations governing where system infrastructure may be installed. Rules constraining where and how collector arrays, tanks, etc., are installed will inform the siting of equipment in subsequent case studies.

The design and construction of residential SWH systems are most heavily regulated by the state of California and local governments. Both California and Los Angeles County have specific system design and performance requirements that must be met for builders to receive construction permits and for systems to qualify for incentive programs (i.e. CSI Thermal). This section includes a summary of those regulations and explains their influence on community scale system design.

The federal government allows states to set their own building codes and performance standards for SWH systems. The Department of Energy and the EPA provide information on best practices for system construction and eligibility requirements for the Residential Renewable Energy Tax Credit. California's requirements for residential SWH system performance overlap with those for the Residential Renewable Energy Tax Credit.

3.1 Industry Codes for System Components

The Solar Rating and Certification Corporation (SRCC) is a nonprofit organization responsible for the testing and certification of solar thermal technologies in the United States. SRCC is a member of the International Code Council, and its testing requirements are based on the International Standardization Organization's (ISO) codes.

The SRCC has two solar thermal technology rating certifications, OG-100 and OG-300. The OG-100 certification program sets standards for the durability and thermal performance of solar thermal collectors. The OG-300 program applies to single-residence

SWH systems, and requires that systems meet an overall standard minimum thermal performance.[101]

OG-100 Solar Collector Certification Program

California requires that all domestic and multi-family SWH systems use solar thermal collectors approved by the SRCC to be eligible for CSI Thermal renewable energy credits. The SRCC's standards and test sequence for solar collectors are known as the OG-100 Minimum Standards.[102] OG-100 makes use of ISO 9806 standards. Separate test sequences exist for FPC and ETC collectors.[103]

The OG-100 certification process consists of laboratory test sequences for different types of thermal collectors. Solar thermal collectors that meet or exceed testing criteria are listed on the SRCC's website. Physical specification and thermal performance data are provided for each unit that receives OG-100 certification.

Table 3: Description of ICC-SRCC OG-100 Solar Collector Production Standards[104,105]

Test Sequence Elements	Description	OG-100 Requirements
Cover	Impact test of tempered/ non-tempered or glazed/ unglazed glass cover (FPC) or outer protective tube (ETC)	No deformation during test sequence. Pass ISO 9806 Impact Test
Fluid Path Pressure Drop	Inspection of Collector tubes/ manifolds. Input and output ports.	No loss of pressure greater than ISO 9806. No serious fluid path deterioration.
Thermal Shock	Water spray test on collector at test operation temperature. Cold fill test of collector tubes/manifold at test operation temperature	No serious deformation of cover or absorber elements. Performance not degraded by moisture penetration.

[101] International Code Council. (2015). *2015 ICC 900/SRCC 300 – 2015 Solar Thermal System Standard.* Retrieved from: https://codes.iccsafe.org/public/document/toc/569/
[102] International Code Council. (2015). 2015 ICC 901/SRCC 100 2015 Solar Thermal Collector Standard. Retrieved from: https://codes.iccsafe.org/public/document/code/570/9961307
[103] *Ibid.*
[104] *Ibid.*
[105] ICC-SRCC. (2017). *Operating Guidelines for Certifying Solar Collectors*. Retrieved from: http://www.solar-rating.org/guidelines/ICC-SRCC_OG-100_Operating_Guidelines_For_Certifying_Solar_Collectors.pdf

High Temperature Resistance/ Stagnation Temperature	High temperature resistance test and determination of stagnation temperature	Collectors must be designed to withstand 1000 hrs./year at stagnation without loss of performance.
Thermal Performance	Delivery of useful heat	Meets ISO 9806 Standards
Incident Angle Modifier	Effect of angle of incidence on performance	Meets ISO 9806 Standards
Thermal Capacity/Time Constant	Collector heat capacity	Meets ISO 9806 Standards
Disassembly and Final Inspection	Inspection of all component parts for damage and wear sustained during test sequence	Meets ISO 9806 standards for condition of system components post-test sequence.

The OG-100 test sequence for PV/T collectors differs slightly from the basic sequence in Table 3. Testing PV/T collectors also includes SRCC 100 standards for the PV cell included in the PV/T unit. The PV/T test sequence also measures the Maximum Power Point (MPP) of the cell. Collector area is calculated as the projected area of both PV and thermal components.[106]

OG-300 Residential SWH System Certification Program

The OG-300 program certifies entire SWH heating system designs. This program is for modular systems that are designed to serve the water heating needs of a single residence.

3.2 California State Building Code

Below is a summary of the state building codes with the greatest impact on SWH system design and siting. Other components of an SWH system, such as plumbing systems, control elements are also subject code requirements, but these do not affect basic system design. Code requirements that influence the selection of collection and storage technologies are discussed below.

Title 24, Section 6 – Building Energy Efficiency Standards

A community scale approach to solar water heating will require the installation of systems that serve numerous residential units. Community scale systems thus need to comply with the multi-family SWH codes of California’s Title 24. The most fundamental

[106] *Ibid.*

of these requirements is that multi-family systems use SRCC OG-100 certified solar collectors, and that they meet the basic eligibility requirements listed in Table 5.

Multi-family SWH systems installed in California are required to meet a minimum average annual solar fraction.[107] Table 4 summarizes the minimum solar fractions required for each of the California Energy Commission's (CEC) climate zones. Because the solar fraction of a system varies depending on insolation levels, meteorological conditions, and the precise details of construction and operation, system modeling methods are used to calculate an approximate value for annual solar fraction. This calculated value must meet or exceed the minimum solar fraction for the climate zone. Calculations must be performed with software approved for use by the CEC. Approved programs include both regression and simulation methods for modeling SWH system performance.[108]

Table 4: Minimum solar fraction by CEC climate zone[109]

Climate Zone	Minimum Solar Fraction
1-9	20%
10-16	35%

Table 5: Eligibility criteria for energy efficiency measures – Solar water heating systems (RA4.4.21)

System Certification Type	Eligibility Criteria
SRCC OG-100	(a) Include all features modeled and generated in the CEC approved solar savings fraction calculation
	(b) The collectors should be installed according to manufacturer's instructions
	(c) The collectors shall be located in a position not shaded by adjacent buildings or trees between

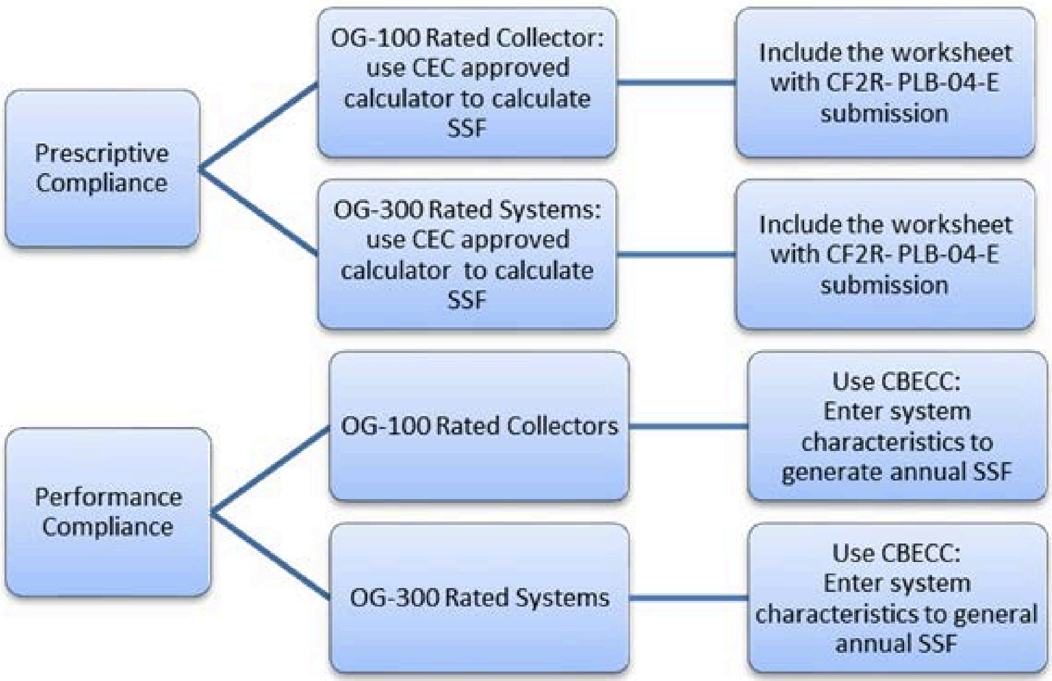
[107] California Building Code. (2016). *2016 Building and Appliance Efficiency Regulations*. Retrieved from: https://energycodeace.com/site/custom/public/reference-ace-2016/index.html#!Documents/59solarwaterheating.htm

[108] Ferris, T., Froess, L., Meyer, C., Ashuckian, D. (2016). *Residential Alternative Calculation Method Reference Manual*. Retrieved from: http://www.energy.ca.gov/business_meetings/2016_packets/2016-06-14/Item07_ACM%20Ref%20Manuals/2016%20Res%20ACM%20Ref%20Manual%20June%202016.pdf

[109] https://energycodeace.com/site/custom/public/reference-ace-2016/index.html#!Documents/59solarwaterheating.htm

	9:00AM and 3:00 PM (solar time) on December 21st.

Figure 14 shows the process flows for prescriptive and performance compliance approaches for solar thermal systems. Selection of an appropriate code compliance approach depends on system scale and design solar fraction. In the case of community scale SWH systems intended to reduce the carbon intensity of water heating, a performance approach is most reasonable.



Figu

A community scale approach to solar water heating requires the installation of collector arrays on multiple residential buildings, including single and multi-family structures. This complicates the task of reaching compliance through a prescriptive approach, as those requirements assume that residential SWH systems only serve a single structure. Therefore, prior to the evaluation of energy savings from community scale SWH systems, solar fraction will be calculated with an approved modeling tool to ensure minimum solar fraction requirements are met.

[110] https://energycodeace.com/site/custom/public/reference-ace-2016/index.html#!Documents/59solarwaterheating.htm

3.3 Los Angeles County Municipal Code

County building permits are required for solar photovoltaic or thermal systems are required prior to construction. The County's "Guidelines for Plan Check and Permit Requirements for Solar Energy Systems", effective since 2015, enumerates the municipal requirements relevant to the design and construction of community scale SWH systems.[111] LA County's guidelines require that SWH systems meet state energy efficiency, plumbing, and electrical codes, in addition to complying with zoning restrictions. The Los Angeles County municipal code does not contain specific SWH system design requirements beyond those in the state code.[112]

3.4 Incentive Program Eligibility Requirements

Community scale SWH systems should take advantage of incentive programs to offset the cost of installation and construction where and when possible. The California Solar Initiative is a subsidy program intended to encourage the proliferation of solar thermal technology for space and water heating.[113] The program lists specific eligibility requirements for multi-family residential systems and systems, summarized in Table 6.

Table 6: CSI-Thermal Incentive Program Eligibility

SWH System Incentive Category	Eligibility Requirements
Multi-family <250 kWth, Commercial/ Multi-family > 250 kWth	**Equipment** • OG-100 certified collectors • Active, indirect system type • System must include freeze and stagnation protection according to CEC climate zone. • Direct or passive systems are ineligible • Storage tanks must have R12 insulation • Flow meters **Installation Requirements** • Fluid collector square footage area cannot exceed 1.25 times estimated GDP (gallon per day) • Systems with two or more tanks must have a minimum of 1 gallon of storage volume per square foot of collector • Systems with (Collector area/ GPD) > 1.25 must provide justification for sizing.

[111] https://www.ladbs.org/docs/default-source/publications/information-bulletins/general/guidelines-for-plan-check-and-permit-requirements-for-solar-energy-devices-ib-p-gi2014-027.pdf?sfvrsn=26
[112] *Ibid.*
[113] California Public Utilities Commission. (2017). *California Solar Initiative – Thermal Program Handbook*. Retrieved from: http://www.gosolarcalifornia.ca.gov/documents/CSI-Thermal_Handbook.pdf

	• R2.6 insulation on all exposed or accessible hot water piping.

4 System Design for Community Scale SWH in Los Angeles County

Specifying a basic community system design is necessary to estimate cost and energy savings in subsequent analyses. Any community scale system must meet the design criteria specified by the CEC, Title 24, and Los Angeles County. Community scale SWH systems should also be eligible for CSI-Thermal rebates to offset capital costs where possible, given the low cost of competing energy sources.

The following sections justify the selection of component technologies and system design elements for community scale systems in LA County. Building code and rebate eligibility requirements, cost, thermal performance, and climactic conditions are all given consideration in the design of community scale systems.

4.1 Solar Fraction Requirements

The CEC requires that multi-family residential SWH systems meet minimum solar fraction requirements. Designer-builders must demonstrate compliance by calculating annual average solar fraction for a system using one of the following listed approved calculation methods. All community scale systems in subsequent case studies will meet the minimum solar fraction requirements for the climate zones in which they are located.

<u>Approved Calculation Methods</u>

The CEC and CSI Thermal programs list approved calculation methods for SWH system solar fractions. Approved programs include both regression and simulation methods for the calculation of solar fraction.

Regression methods use performance data from large numbers of thermal hydronic systems to estimate solar fraction. Estimates of solar fractions are based on empirically determined relationships between system design characteristics and thermal performance. The most widely used regression method is the f-chart method. This method uses meteorological data and system specifications to estimate an average annual solar fraction.[114] The CEC's Title 24 Calculator for multi-family is based on the f-chart method, and is approved to demonstrate prescriptive compliance with solar fraction requirements.

Simulation methods for calculating solar fraction model the thermal performance of buildings, including solar thermal systems, from first principles. This method is preferred

[114] California Energy Commission. (2016). *Solar Water Heating Calculation for Build Up Systems*. Retrieved from: http://www.energy.ca.gov/title24/swh_calculator/

when a designer-builder of a SWH system prefers a performance pathway to compliance with Title 24. The California Building Code Compliance Software (CBCC-Res) for Low-Rise Residential Buildings is the simulation software offered by the CEC for this purpose.[115] This method requires detailed information about building characteristics and SWH system specifications to estimate solar fraction.

4.2 Selection of Community Scale SWH System Components

Estimating the energy savings from community scale SWH systems requires the selection of appropriate component technologies for the given application and climate. To establish compliance with minimum solar fraction requirements, the following must be specified:

- **Collector Type**
- **Active/ Passive System Type**
- **Direct/ Indirect System Type**
- **Thermal Energy Storage Duration**
- **Auxiliary Heat Source**

<u>Integral Collector Storage and PV/T</u>
Based on the review of commercially available solar thermal collectors, flat-plate and evacuated tube collectors are potentially suitable for community scale SWH systems in LA County.

ICSS and PV/T are not suitable for community scale SWH. Integrated collector storage systems exhibit highly variable solar fractions, and are better suited for use within the context of individual residences. Additionally, building code requirements such as rooftop load limits and minimum solar fraction disqualify such systems.

While PV/T collectors provide an elegant solution to the problem of PV and thermal systems competing for rooftop space, the cost and durability of existing PV/T cell technologies make them unattractive for community scale applications. PV/T panels are less thermally efficient than solar thermal collectors, thus a solar water heating system with PV/T panels must have a larger collector area than a purely thermal system to meet an identical load.[116] PV/T collectors are also more expensive on the basis of dollars per installed unit of collector area than either FPC or ETC technologies.[117] Table 7 shows a comparison in terms of dollars per square meter.

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[115] Ross, D.A. (2016). *CBECC-Res 2016 User Manual: For California Building Energy Compliance Public Domain Software*. California Energy Commission. Retrieved from: http://www.bwilcox.com/BEES/docs/2016%20CBECC%20User%20Manual%20Sep%202016.pdf

[116] Dean, J., McNutt, P., Lisell, L., Burch, J., Jones, D., Heinicke, D. (2015). *Photovoltaic-Thermal Technology Demonstration.* NREL. Retrieved from: https://www.nrel.gov/docs/fy15osti/63474.pdf

[117] Matuska, T. (2014). ScienceDirect Performance and economic analysis of hybrid PVT collectors in solar DHW system. *Energy Procedia*, *48*, 150–156. https://doi.org/10.1016/j.egypro.2014.02.

Collector Type	$/ m^2
PV/T	$531-$1121[118]
FPC or ETC	$59-$223[119]

Table 7: Cost per square meter of installed collector area – PV/T vs. Thermal

With regards to durability, the materials used to construct some PV/T collectors limits their operational temperature to 130-170^{o}F.[120] PV/T collectors with EVA laminated PV cells may be damaged by prolonged exposure to temperatures at or above 130^{o}F, as EVA thermally degrades above this temperature.[121] FPCs and ETCs have much higher stagnation temperatures, between 180-210^{o}C and 220-300^{o}C, respectively.[122] Furthermore, SRCC OG-100 Standards require that collectors be able with withstand 1000 hours of stagnation temperature per year without serious performance degradation. Thus, given the cost and accelerated timetable for performance degradation relative to thermal collectors, PV/T collectors will not be used in the community scale SWH systems proposed in this effort.

<u>FPC vs. ETC</u>

The choice of collector technology for community scale systems in LA County may be narrowed to FPC or ETC. The choice the optimal collector technology may be made on the basis of climatic conditions and cost.

Climatic conditions in LA County favor FPCs over ETCs. Figure 15 shows steady-state and daily thermal efficiency curves for both evacuated tube and flat-plate collector types. Thermal efficiency is plotted as a function of the difference between ambient and fluid inlet temperature (reduced temperature) normalized by the level of incident radiation. Daily thermal efficiency measurements were made in Padova, Italy. The thermal efficiency of ETC is less sensitive to changes in ambient or inlet temperature, and outperform FPCs when the difference between ambient and fluid temperatures is large.[123] However, FPCs are more efficient that ETCs when this difference is small, and when weather conditions are relatively mild. FPCs are

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[118] *Ibid.*

[119] https://www.epa.gov/rhc/rhc-multi-unit-housing#Footnotes

[120] Zondag, H. A., & Van Helden, W. G. J. (n.d.). *Stagnation Temperature in PVT Collectors*. Retrieved from http://www.ecn.nl/docs/library/report/2002/rx02045.pdf

[121] *Ibid.*

[122] Hausner, R., Fink, C. (2002). *Stagnation Behavior in Solar Thermal Systems.* International Energy Agency – Solar Heating & Cooling Programme. Retrieved from: http://www.aee-intec.at/0uploads/dateien48.pdf

[123] Zambolin, E., & Del Col, D. (2010). Experimental analysis of thermal performance of flat plate and evacuated tube solar collectors in stationary standard and daily conditions. Solar Energy, 84(8), 1382-1396.

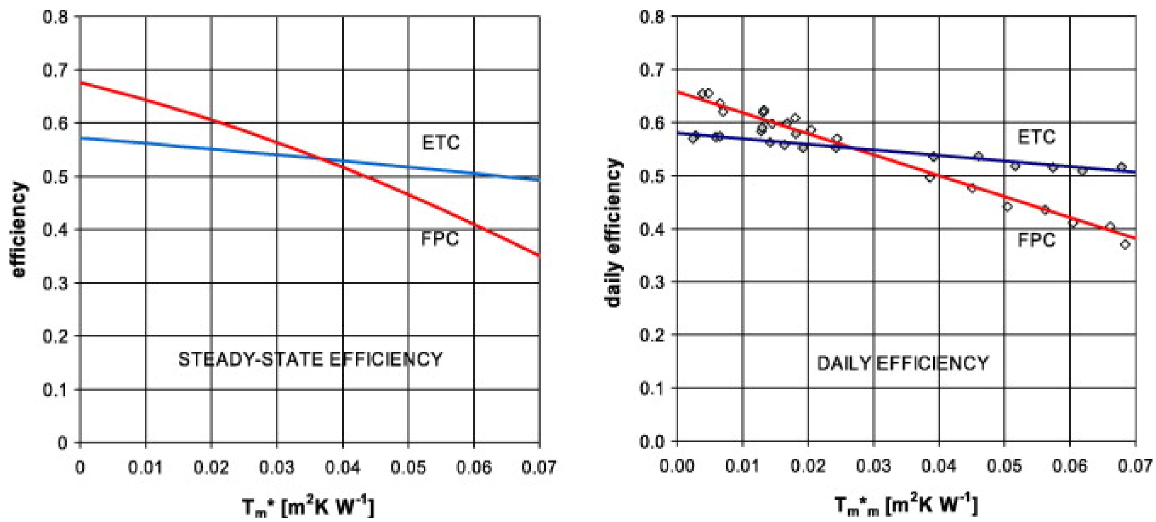

Figure 15: Thermal efficiency vs. reduced temperature (T_a-T_I) for FPCs and ETCs under steady-state and field conditions in Padova, It.[124]

Cost considerations also favor FPCs. FPCs are 20-40% cheaper than ETCs per collector unit, as they are less materially intensive to manufacture.[125] FPCs will be the default collector type for community scale SWH systems in LA County.

Active/ Passive System Type

Community Scale SWH systems will feature centralized storage of hot water to increase thermal efficiency. Distribution of hot water and recirculation within residential buildings necessitates that community scale systems be active. Pumps are required to deliver water to residential units.

Direct/ Indirect System Type

As mentioned previously, direct systems are not eligible for energy credits as per the CSI-Thermal Program Handbook.[126] Therefore, community scale SWH systems will be indirect to take advantage of the available incentives. Community scale systems considered in this analysis may therefore be classified as “indirect forced circulation” systems. Indirect forced circulation systems use pumps to circulate a working fluid within the collector array. Thermal energy is transferred to potable water through a heat exchanger.

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124 *Ibid.*

125 Solartown. (2016). *Solar Water Heater Choices: Flat or Evacuated Tube Collectors?*. Retrieved from: https://solartown.com/learning/solar-water-heaters/solar-water-heater-choices-flat-plate-or-evacuated-tube-collectors/

126 California Public Utilities Commission. (2017). *California Solar Initiative – Thermal Program Handbook*. Retrieved from: http://www.gosolarcalifornia.ca.gov/documents/CSI-Thermal_Handbook.pdf

Thermal Energy Storage Duration
The volume of thermal energy that a community scale solar thermal systems energy must store, and the duration over which it must store it depends on seasonal variation in the supply of and demand for energy.

Regarding the supply of solar energy, The National Renewable Energy Laboratory (NREL) estimates that Los Angeles County receives enough sunlight for a base case SWH system (a single residence with constant load and electric auxiliary heater) to achieve an annual solar fraction >80%.[127] This suggests that seasonal variation in the intensity and duration of incoming sunlight is not sufficient to warrant the construction of large and expensive seasonal heat stores, and that community scale systems will be able to meet and exceed minimum solar fraction requirements year round, though solar fraction may fluctuate seasonally.

Auxiliary Heat Source
Community scale SWH systems must be able to provide hot water to the residences it serves in the event of extended inclement weather or temporary system shutdown. As the selection of an auxiliary technology will only affect energy savings (gas vs. electric) and the capital cost of a system, rather than its thermal performance, this question will be treated in subsequent case studies.

5 Conclusion

Based on LA County's regulatory environment and climate, a closed, active system with centralized storage of hot water, and a flat-plate collector array appears to be the most suitable configuration for community scale SWH systems in Los Angeles County. Such systems are easily scalable, and may be thought of as "micro-utilities", providing hot water to residential units.[128]

This analysis is not intended to provide a method for designing an energetically and economically optimal SWH system design for any case, but to present a feasible community scale system design appropriate for Los Angeles County. Establishing the basic features of putative community SWH systems is necessary to model their thermal performance.

A full discussion of the details of heat supply and demand modeling will be forthcoming in the **Methodology Report**.

[127] Cassard, H. Denholm, P., Ong, S. (2011). *Break-even Cost for Residential Solar Water Heating in the United States: Key Drivers and Sensitivities.* NREL. Retrieved from: https://www.nrel.gov/docs/fy11osti/48986.pdf
[128] Chen, William. (2017 Oct. 20). Personal Communication.