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Publication Date
2021-06-01

DOI
10.1016/j.renene.2021.02.031

Peer reviewed

Renewable Energy 170 (2021) 1081–1095

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Residential solar water heating: California adopters and their experiences

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ARTICLE INFO

Article history:
Received 26 November 2020
Received in revised form
4 February 2021
Accepted 5 February 2021
Available online 14 February 2021

Keywords:
Solar water heating
Residential
Household
Consumer adoption
Barriers

ABSTRACT

Solar water heating provides domestic hot water with lower greenhouse gas emissions compared to more typical natural-gas water heating. Solar water heating has a long history, particularly in places where the climate is favorable, such as California where state-backed incentive programs have been successful in creating small bursts of adoption. However, widespread adoption of solar water heating has not occurred in California despite these conditions. This research surveyed 227 single-family households with solar water heating across the state of California to understand their motivations and experiences, and draw implications regarding barriers to adoption. The survey explored households' experiences across five stages of adoption, as outlined in Rogers' Diffusion of Innovation theory: Knowledge, Persuasion, Decision, Implementation, and Confirmation. Findings revealed challenges at each stage. Most notably, prevalent disappointment in lower-than-expected energy and bill savings (31%) and high rates of technical problems (41%) appear to be the most significant issues.

1. Introduction

Climate experts report that natural gas dependency contributes to the rise in planet-warming carbon emissions [1]. Natural gas accounts for roughly 19% of the US residential sector's total energy consumption most of which is used for space and water heating [2]. California's dependence on natural gas for residential energy (24% of total consumption) is greater than the national average, with 40% used for water heating.

Solar water heating (SWH) can be a useful alternative to natural gas-fired water heating, involving relatively low fuel input, minimal greenhouse gas emissions, and potentially low equipment and maintenance costs [3,4]. In theory, SWH could reduce natural gas use by as much as 50–80% depending on how hot water usage aligns with production and storage capacity [5,6]. A recent evaluation of California SWH installations found that savings were higher for commercial and multifamily installations than single-family residential [7].

While still accounting for a small fraction of total water heating needs, SWH plays a significant role in a growing handful of countries and regions [8]. Globally, SWH installations in 2018 totaled 480 GWTh of SWH capacity, yielding 396 TWh of solar thermal energy across all applications (i.e., residential, commercial, industrial, and agricultural). Numerous European countries have adopted SWH as a primary source of residential water heating [9]. By contrast, SWH in the US remains relatively uncommon, with just a few states (Florida, Hawaii, and California) being modest exceptions [10].

California has a long history of SWH and SWH-friendly legislation. Over the last 130 years, SWH has had several waves of niche popularity in California. However, despite a mostly favorable climate, advances in technology and aesthetics of SWH units, and generous, state-backed incentive programs, SWH adoption remains low. This research sought to deepen our understanding of the characteristics, motivations, and experiences of SWH adopters in California. The research study reported herein was one component of a larger holistic study of SWH in single-family homes in California [11]. That project included a historical review of SWH in California [6], which is summarized in the next section, interviews with industry stakeholders, and a survey of adopters (the focus of this paper).

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https://doi.org/10.1016/j.renene.2021.02.031
0960-1481/

2. History of solar water heating in California

In 1891, the "Climax," the first commercial solar thermal water heater for homes, was patented. The Climax, described as the "acme of simplicity" for providing hot water, did not require the hard labor associated with traditional coal and wood-fired water heating [12]. In addition, it seemed especially promising for Southern California because of its favorable climate and high fuel costs [12]. By 1900, there were reportedly 1600 homes with SWH in Southern California.

Around the same time, the development of household gas water heating was underway. While both gas and SWH technologies continued to develop, solar thermal experienced a devastating blow. In 1913, a hard freeze in Southern California destroyed many solar water heaters, which coincided with the discovery and recovery of cheaper natural gas. These events, combined with natural gas utilities efforts to make water heaters affordable, led to a shift toward natural gas. By the 1930s, natural gas water heating dominated in California, and SWH faded into the background.

Energy crises in the 1970s and 1980s sparked renewed interest in solar technologies [13]. The Carter Administration introduced tax incentives for SWH, generating an increase in demand. When the Reagan Administration removed incentives, the market mostly fell apart [14]. According to the American Housing Survey, the number of US households that had SWH systems steadily fell from 1985 to 2000, after which it remained level at around 140,000 [15].

There was another resurgence when the California Solar Initiative, initially launched in 2006 to promote solar photovoltaic (PV), expanded to include SWH through the Solar Water Heating and Efficiency Act of 2007. The California Solar Initiative-Thermal program (CSI-T), piloted in 2007–2009 as the California Solar Water Heating Pilot Program (SWHPP), launched in 2010 and continued to incentivize the SWH installation for investor-owned utility customers, and provide system and installation specifications and recommendations, training, and public data until the summer of 2020 (Fig. 1). Designed to address problems SWH encountered during the 1980s, the CSI-T program required SWH systems to have a 10-year warranty to be eligible for the incentive [16].

Initial uptake of the CSI-T incentives among single family homes was slow as the out-of-pocket costs remained higher than a standard water heater replacement and most installers were not offering or promoting SWH. In 2017, in response to the Aliso Canyon Gas Storage Facility well failure, the CSI-T incentives were raised for the Southern California Gas Company territory. Seeing an opportunity, a single installer in Los Angeles began an ambitious door-to-door sales campaign, leveraging prior experience with a utility program. They mostly targeted low-income households, for whom they were able to install SWH systems for a nominal fee. The installer was able to charge little more than the incentive by installing less expensive SWH configurations and purchasing them in relatively high volumes. These now account for more than half of all CSI-T SWH installations using natural gas backups. By contrast, about a quarter of households (mostly from the early years of the program) paid $7000 or more out-of-pocket for their systems, though many received a 30% federal solar tax credit, reducing their final cost. The result is a diverse portfolio of projects and participating households, reflecting the evolution of the program.

3. Literature review

The literature on residential SWH adoption includes assessments of macro-level factors that shape the environment for SWH adoption. In an industry analysis of SWH in the US, Fitzmorris found adoption is hindered by high upfront system costs, lack of a single dominant technology, lack of access through traditional distribution channels (e.g., retail stores, contractors), and multiple pathways to dissemination (i.e., builders for new construction and homeowners for existing stock) [15]. A 2012 NREL report argued that industry certifications and stakeholder education are critical for encouraging solar technology more broadly [17]. Incentives, which change over time as reviewed above and vary geographically, including within the US, can help address high upfront costs [18].

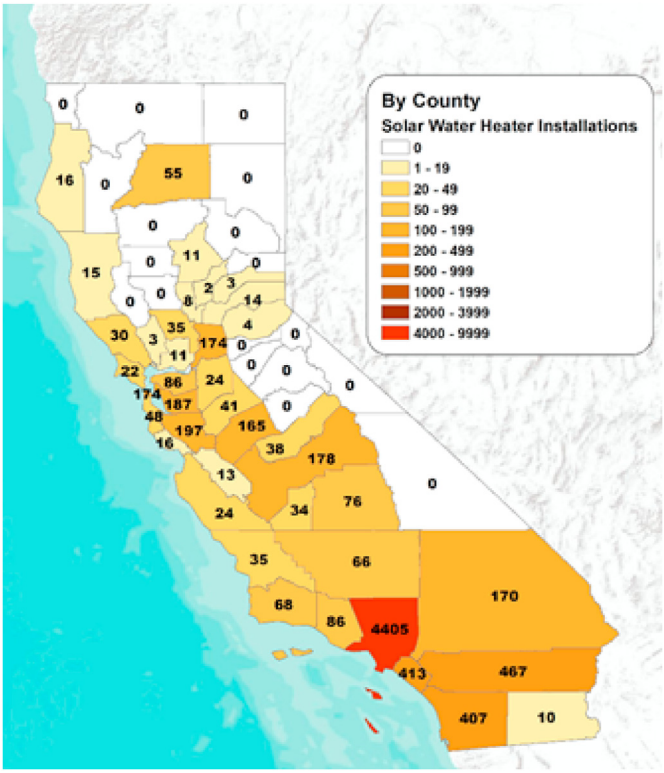

Fig. 1. CSI-T-incentivized single-family SWH installations with natural gas backup systems, as of March 6, 2018.

3.1. Adopter characteristics

Consumer-focused SWH adoption studies have been sparse, particularly in the US. A flurry of attention to residential solar thermal adoption in the 1970s (for space, water, and pool heating) was summarized in a review by Vories and Strong providing interesting comparison points for the current study [19]. Concerning adopter characteristics, they found that solar-thermal-adopting households had higher income and education compared to the national average; were typically young to middle-aged (25–50) professionals, managers, or white-collar workers with small families; and largely self-identified as Republicans or conservatives. A few of these factors seem to remain important: Schelly found that SWH adoption is higher in US counties with higher income and education levels, lower unemployment, and greater environmental values (in addition to suitable climates) [20]. In keeping with the latter, a much higher percentage of SWH adopters from the California SWHPP also had photovoltaic (PV) systems (38%) compared to non-adopters in the same region (10%).

3.2. Motivations and barriers

In the studies reviewed by Vories and Strong, SWH adopters were motivated by saving on utility bills, saving energy, and protecting the environment [19]. One of the studies reviewed was an

in-depth exploration of nineteen residential solar-thermal adopters in Palo Alto, California [21]. From interviews, the research identified four "types" of SWH adopters: (1) Ecologists (environmentally motivated), (2) Tinkerers (who enjoy working with new technologies), (3) Comfort/Convenience Seekers (who enjoyed guilt-free home or pool heating), and (4) Economy-minded.

A more recent study focused on single-family households in the San Diego area, both with and without SWH [22]. Among the sample of SWH-adopting households, who were participants in the California Solar Water Heating Pilot Program (SWHPP), environmental concern was the most oft-cited motivation (58%), with energy savings and financial incentives a close second (each 56%). Households without SWH systems in the Itron study were most interested in the ability of SWH to reduce energy bills [22].

Consumer studies outside the US have yielded similar findings. Regarding the differential motivations of adopters versus considerers, Woersdorfer and Kaus found that environmental motivation drove the decision to adopt among the earliest adopters in Germany [23]. In contrast, those considering adoption were more influenced by financial and social factors (See Mills & Schleich, and Welsch & Kühling) for more on SWH adoption in Germany [24,25]. All the motivations for residential SWH adoption described in the above studies align with broader assessments of renewable energy adoption intentions (e.g., Engelken et al. [26]).

In terms of barriers to adoption, Itron found that non-adopters were most concerned about installation costs, echoing the findings of NREL from a survey of homeowners without SWH in Florida, Arizona, and California [22,27]. Outside the US, Grieve et al. conducted in-depth interviews with homeowners in New Zealand who were purchasing a home, renovating, or replacing a water heater (representing the significant opportunities for SWH adoption) [28]. They found that a major barrier is the homeowner's responsibility to drive the SWH adoption decision from start to finish with little support from relevant tradespeople who instead promote the status quo technology and know little about SWH. Similarly, a survey of SWH adopters and considerers in the UK found that lack of trustworthy information and reliable brands were significant barriers to adoption, along with high upfront capital costs [29].

3.3. Experiences

These studies focused primarily on motivations, barriers, and contextual factors related to the SWH purchase decision. Less attention has been given to understanding additional aspects of adopters' full experience, from awareness to purchase to installation, use, and satisfaction with various performance dimensions. For example, Itron asked SWHPP participants about their procurement, installation, and rebate process experiences [22]. Problems were relatively common (experienced by 39%), most often related to contractors or the permitting process, even in the context of their small pilot project that might have afforded consumers with more support than they would have had otherwise.

Vories and Strong's review revealed that, although most adopters seemed satisfied, they had no idea how well their systems were performing or how much energy and money they were saving [19]. An in-depth adopter study in Australia found that post-installation outcomes were multi-faceted and diverged between active and passive users [30]. Passive users viewed SWH installation as an 'end' rather than a means of saving energy and money, assuming the promised savings would automatically be generated regardless of how they use the system. Active users were more engaged in experimentation to maximize the use of solar heating and associated savings, for example timing their hot water use and using the "booster switch", a feature on some SWH systems to control the backup heat source. Passive users had less efficient systems, but active users were less satisfied with their systems. Contributing to both of these negative outcomes was a lack of information and ability to monitor the complex systems, resulting in gas or electricity savings below householder and policy expectations.

The present research aimed to assess the full adoption process among single-family homeowners in California, associated with the most recent policy effort to promote SWH in the state [29,30]. Similar to Grieve et al. and Woersdorfer and Kaus, we used Rogers' Diffusion of Innovation (DoI) theory as a framework for our study [23,28,31]. However, we used a different DoI element than these other studies: the Innovation-Decision Process (see Sanguinetti et al. for an application of this framework to consumer adoption of smart home technology [32]).

4. Methods

Rogers' Innovation-decision Process provides a framework for understanding how an individual moves from having knowledge about an innovation to the decision to reject or adopt and then implement a new idea or technology, and the confirmation of their decision thereafter [31]. This framework focuses on the intrapersonal process, differing from the interpersonal process that happens across different groups (e.g. adopter categories including: innovators, early adopters, early majority, late majority, and laggards). Rogers identifies the following stages in the process:

1. **Knowledge Stage:** Awareness and understanding of the technology;
2. **Persuasion Stage:** Attitudes regarding the degree to which the technology aligns with one's needs and values, relative to alternatives;
3. **Decision Stage:** Actions leading up to and including technology purchase or acquisition;
4. **Implementation Stage:** User experience after acquisition; and
5. **Confirmation Stage:** Reassessment of the degree to which the technology aligns with the user's values and goals (mirroring the Persuasion Stage).

This process is linear in the sense that one cannot get to later stages without experiencing preceding ones, although the stages can overlap (e.g., knowledge can continue to develop during implementation). This framework supports our goals to explore adopter experiences and uncover barriers at all stages of the adoption process.

An online survey was conducted with California single-family households with SWH who received incentives for installing solar water heating under the CSI-T program. Questions targeted each of the five Innovation-Decision stages (see Appendix A), as well as hot water use habits and household characteristics. The survey included both closed and open-ended questions.

Participants were identified via CSI-T program data provided by the California Public Utilities Commission. Because the research was funded with natural gas research money, we focused on single-family households with natural gas as the backup water-heating source, which is also by far the most common in California.[1] Of the 4002 households meeting these criteria, 1922 were recruited to participate in the survey, using a stratified sampling approach to increase the representation of different utility territories, installing contractors, and the Low-Income CSI-T Program.

[1] Fourteen households were excluded because they were the subject of an ongoing detailed performance evaluation, and we wished to avoid influencing participants' behavior or burdening them with additional demands.

Households for which an email address was available ($n = 825$) were invited via email and received a reminder one week later. The remaining were recruited via postal mail, with no reminder. The final cleaned survey dataset included 227 households, about a 12% response rate overall (6% for postal mail; 21% for the email). Twenty-two incomplete responses were removed. (Responses were considered incomplete if questions on the last two pages of the survey were blank and if there were no responses to open-ended survey questions.) We also excluded four households that moved in after SWH installation and two where a property manager made the decision.

5. Results

Table 1 summarizes survey respondents' household and SWH system characteristics (per survey respondent self-report except where noted). Most households (80%) reported having a standard SWH system that was working (91%) and had been installed by a hired professional (94%). The majority were located in PG&E territory (i.e., Northern and Central California), which was over-represented compared to CSI-T participants more broadly.

Table 2 describes survey respondent demographics. Households with members that have professions suggestive of an affinity towards or prior exposure to SWH accounted for 68% of respondents. Our sample included more males than females and was slightly older, including more retired persons than General Social Survey (GSS) respondents living in detached dwellings.

5.1. Knowledge

Respondents were diverse in terms of how they learned about SWH, often through someone who worked on their home (i.e., a plumber, contractor, architect, or solar installer; 21%); a friend, family member, or acquaintance with SWH (18%); or various media (e.g., magazines, Internet; 15%). Some (8%) had long known about SWH, since childhood in some cases or through their profession, whereas others (8%) learned about it for the first time from local government, utility company, or community resources; and about 9% learned about it from a SWH manufacturer or retailer. When asked about ease of access to information about SWH, one-quarter to one-third of respondents felt it was challenging to find information across multiple aspects of SWH (Fig. 2).

5.2. Persuasion

We asked respondents to describe in a few words their motivation for acquiring SWH. Themes included saving money (particularly over the long term) and environmental concerns – often in conjunction (e.g., "cost savings and utilizing renewable energy for environmental purposes"). Other themes included energy independence, appropriateness for climate (ample sunshine), and the potential for plentiful or inexpensive hot water. Feedback reflecting these motivations included responses such as "We live in a sun-filled climate, and it just doesn't make sense to me NOT to install a system that takes advantage of that," and "It gives almost free hot water!" Several respondents also referenced solar PV, noting they had installed PV and SWH together or installed SWH after installing or considering PV. One noted the combination allowed them to "have a house almost free of imported energy." These themes were reinforced in closed-ended responses (Fig. 3). Only 22% said they would have installed SWH if the rebate had not been available (59% said "No"; 20% said "Maybe").

The most common concerns pertained to the high initial cost, reliability, potential home damage, performance, and return-on-investment (Fig. 4). Open-ended comments also included concerns about lack of roof space, roof replacement, lack of qualified local contractors, and the need for approval from a Home Owner's or Condominium Owner's Association (HOA/COA).

5.3. Decision

The Decision Stage includes the rebate and installation processes and other contextual factors, such as decision-making about home upgrades. As shown in Fig. 3, conversations with salespersons, contractors, and acquaintances who own SWH, as well as doing other work on the home, including considering PV, were relatively common actions precipitating the adoption decision. Nearly half the sample (47%) had PV. Of those households with PV, nearly half (48%) had PV before they acquired SWH, 30% acquired PV and SWH around the same time, and 21% acquired SWH before

Table 1
Survey respondents' SWH and household characteristics.

SWH Characteristics		Household Characteristics	
Current Condition of SWH	92% Working	**Year House Built**	13% Before 1950
	3% Removed, disconnected, broken		23% 1950s
	3% Not sure		11% 1960s
	3% Other (e.g., waiting on a part, moved away)		19% 1970–1982
			10% 1983–1992
			16% 1993–2004
			9% After 2004
Acquisition of SWH	96% Hired installer	**Square Footage**	7% 1000 or less 23% 1001–1500
	4% DIY install		29% 1501-2000
			17% 2001-2500
			11% 2501-3000
			9% 3001-4000
			4% More than 4000
Type of System Replaced	80% Standard tank	**Natural Gas Utility**	53% PG&E
	7% Different SWH		34% SoCalGas
	5% Tankless		10% SDG&E
	4% Electric heat pump (hybrid)		2% Other (survey invitation likely sent to a new address)
	2% High-efficiency condensing		
	2% Not sure		
Year of Install	25th percentile = 2012	**CSI-Thermal Incentive Program**[a]	80% Single-family
	Median = 2015		20% Low-income single-family
	75th percentile = 2016		

[a] Surveys matched with CSI-T dataset to determine incentive program.

Table 2
Survey respondent demographics compared to general population demographics.

	SWH Survey Sample	General Population
Household Size	Mean = 3.3 25th percentile = 2 Median = 3 75th percentile = 4	Mean = 2.75[a] 25th percentile = 2 Median = 2 75th percentile = 4
Housing Tenure	96% Own 4% Rent	77% Own[b] 23% Rent
Household Income	25th percentile = $50,000–74,999 Median = $100,000–149,999 75th percentile = $150,000–199,999	Median = $71,805[b]
Rooftop Solar PV	47%	9%[c]
Member w/Related Profession	**44%** None of the above 22% Engineering 16% Construction, Housing, Real Estate 15% DIY Home renovation 12% Biology, Chemistry, Envir. Sciences 10% Energy, Planning, Policy 10% Machining, Mechanics, Maintenance 5% Farming or Agriculture	
Retired or Semi-retired	22% One member of Hh 19% Two or more members of Hh	16% of respondents
Gender	61% Male 38% Female 1% Other	45% Male[a] 55% Female
Age, Mean (SD)	55 (14)	48 (17)[a]

[a] 2016 General Social Survey, Smith et al. [33]. Detached dwelling households in the US.
[b] US Census Bureau [34]. Income data for California only.
[c] 2017 US Dept. of Energy reports for California single-family homes [35].

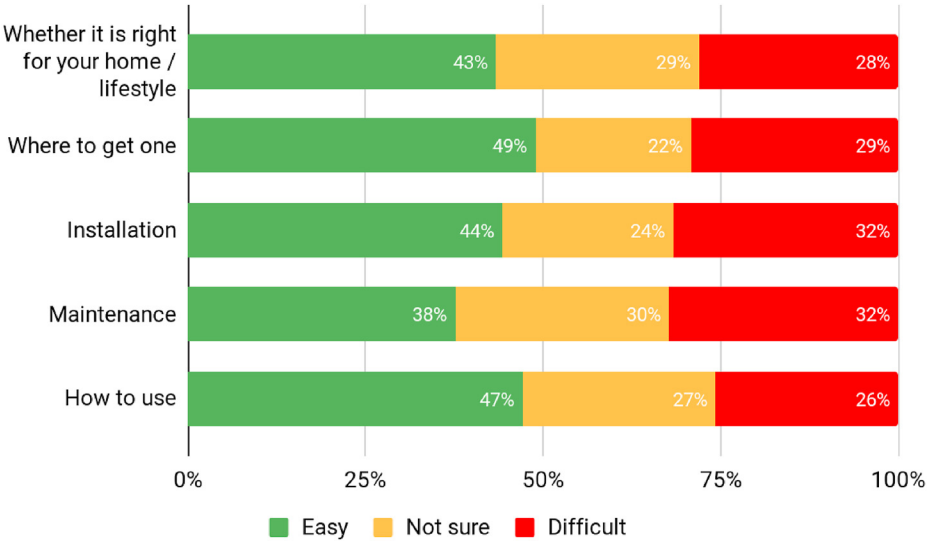

Fig. 2. "Do you think good information about the following aspects of solar water heaters are easy or difficult to find?".

PV (1% were "unsure").

Regarding rebate procurement, most (89%) reported no difficulties; 10% reported uncertainties, communication problems, delays, or changes in the rebate process or availability. Miscommunication most often included the manufacturer or contractor failing to provide proper documentation. For example, one respondent reported, "The contractor forgot to give the city the updated plans on the system, so we failed the first inspection."

Problems during the installation process were more common (Fig. 5), with 41% of adopters experiencing at least one difficulty. Many issues were associated with the installer. In open-ended comments, participants reported installers were often not locally available, inexperienced, messy, or made serious errors with sealing, insulation, and proper pipe placement. Issues related to roof space and layout (particularly if sharing space with PV) and pitch and shading were also relatively common. Other issues included the roof unit's weight (requiring extra cost to reinforce and permit) and the tank's size (making it hard to find space in the garage or violating zoning regulations). Issues with HOA/COA approval were also noted several times.

5.4. Implementation

Implementation includes SWH use, maintenance, and repairs. When asked how they learned to use and manage their system, respondents most frequently said their contractor told them, while one-quarter referred to a user manual, and one in five did not think there was anything *to* learn about it (Fig. 6). In open-ended responses, some participants mentioned wanting more information (e.g., contractors did not give enough information or went out of

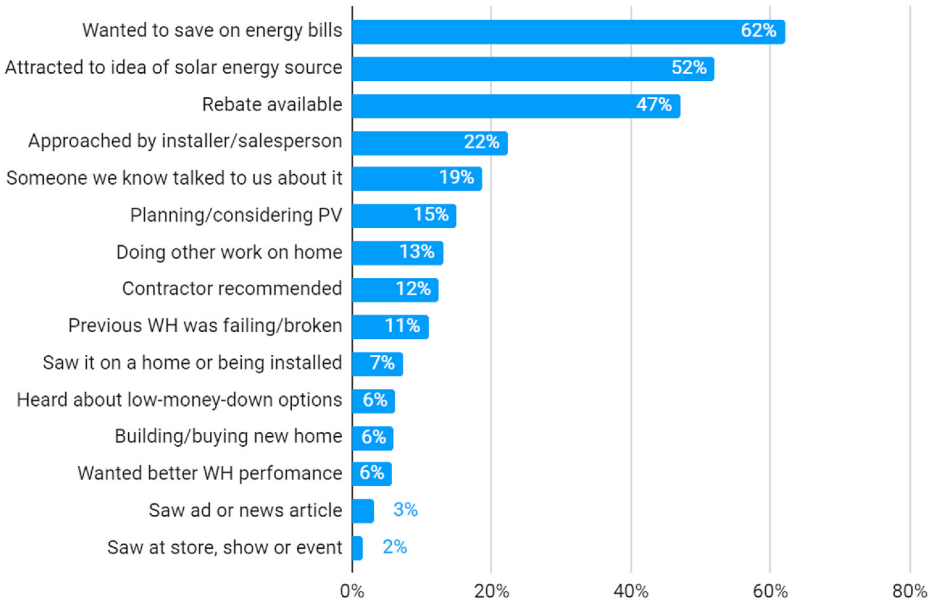

Fig. 3. "Which of the following influenced you to install solar water heating?"

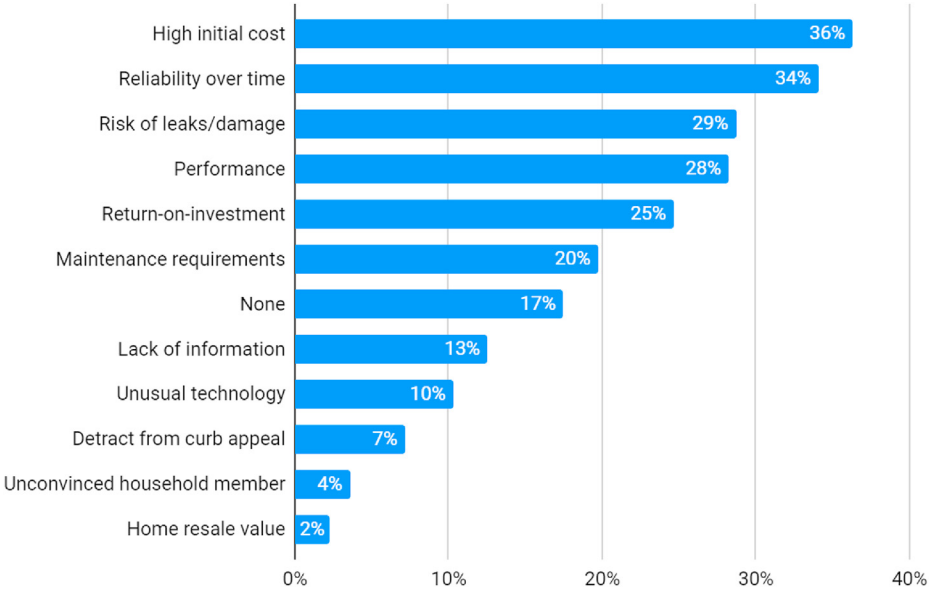

Fig. 4. "What concerns, if any, did you have when deciding to install a SWH?".

business, making follow-up impossible). Others already possessed relevant knowledge from their profession/occupation, and a couple of respondents mentioned they had a monitoring system (e.g., temperature sensors on the equipment and a display).

Most respondents (74%) reported that having SWH has not changed how much hot water they use. A minority (10%) were unsure or thought the question was inapplicable (2%). Few respondents (4%) reported using less water after getting SWH. More respondents (10%) reported increasing their hot water usage, most commonly giving the following reasons: it is more plentiful ($n = 15$), costs less ($n = 10$), and feels less wasteful because it is from renewable energy ($n = 10$). Shifting time of use was slightly more common (16%), moving showers, dishwashing, and laundry to midday or evening to take advantage of SWH. One respondent reported: "I shower in [the] afternoon and wash clothes and dishes during the day on sunny days to avoid having the system blow off excess heat." Some respondents even noted specific times or timeframes for using hot water, e.g., "I like to take a shower around 1 PM to maximize the free heat in the system and be able to recharge it with plenty of light left." Participants also described changing their usage during the winter months (e.g., "[We do] laundry using cold water in winter to avoid using [the] electrical booster element"); "[Our] system is set to be hot in the morning and evening, so we avoid taking showers during the day in the winter."

Most respondents (88%) reported that they do not adjust their SWH when away from home for a long time. Those who did report adjusting mentioned setting to vacation mode, opening the bypass valve, unplugging, covering collectors/solar panels, or turning off the pump. Similarly, most (78%) reported that they never change their backup water heater settings.

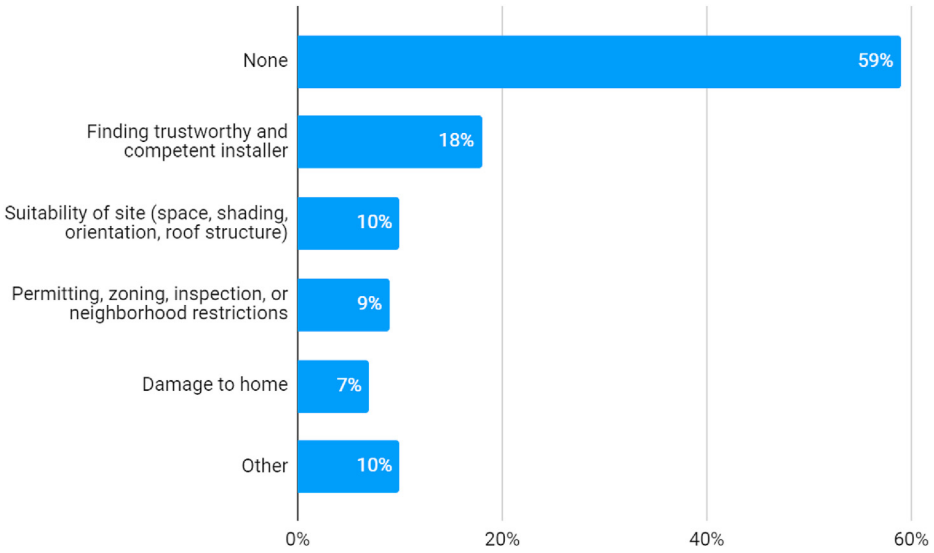

Fig. 5. "What difficulties did you have during the installation of your SWH?".

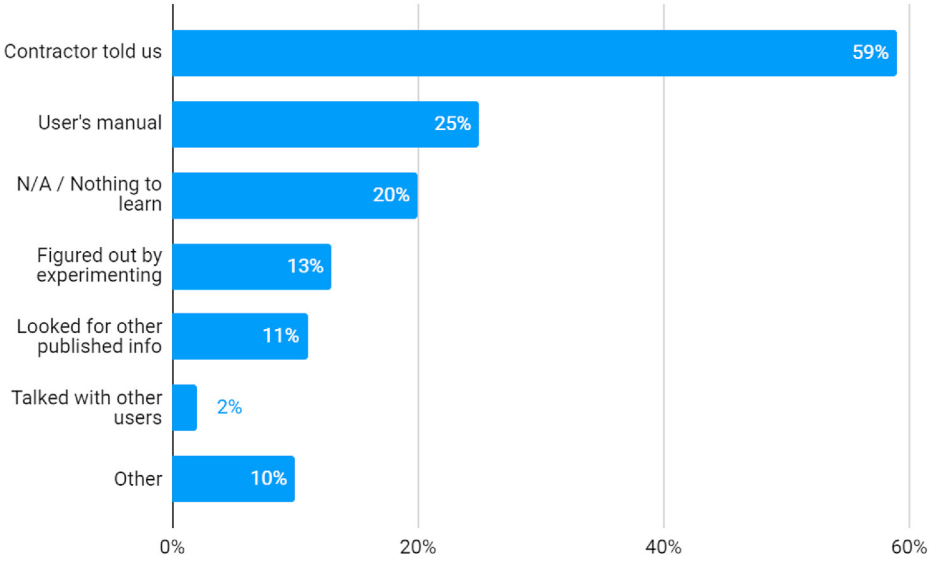

Fig. 6. "How did you learn how to use and manage your solar water heating system?".

In terms of maintenance, 46% said no maintenance work had yet been performed, though many systems were installed only in the past few years. Looking only at households that installed their system before 2014 (n = 81), 46% reported maintenance was extremely easy; 28% somewhat easy; and only 6% said it was somewhat or extremely difficult (14% neutral; 6% "too soon to tell"). This sub-sample reported the following maintenance measures: washing collectors (25%); flushing and replacing antifreeze/glycol (28%); and system inspection (38%). Forty-two percent were satisfied with contractors' availability to provide maintenance and repairs; 20% were not satisfied; 38% selected "Not sure" or "Not applicable."

Of all households, 41% reported at least one issue with SWH performance (Fig. 7). Problems included leaks and unspecified installer errors (12% each), general failure to perform (9%), and issues with the backup water heating system (7%). Other problems specified in open-ended comments included performance insufficiencies or inconsistencies and issues with the pump, as well as 1–2 mentions of each of the following: airlock/insulation, temperature regulation, noise, the feedback/management web application, clogged glycol lines, equipment recall,[2] failed solar collectors, failed valve, and failed temperature gauge. Of those reporting at least one problem, 26% characterized the issue(s) as serious, 30% as moderate, and 38% as minor (5% unsure). Overall, this equates to about 11% of respondents having had serious problems and 12% having had moderate problems with their SWH systems.

5.5. Confirmation

We asked respondents how satisfied they were with various

[2] We know from previous studies that one particular model of SWH systems installed through the CSI-Thermal program had experienced widespread problems and was later de-listed and replaced [6,11,38,39].

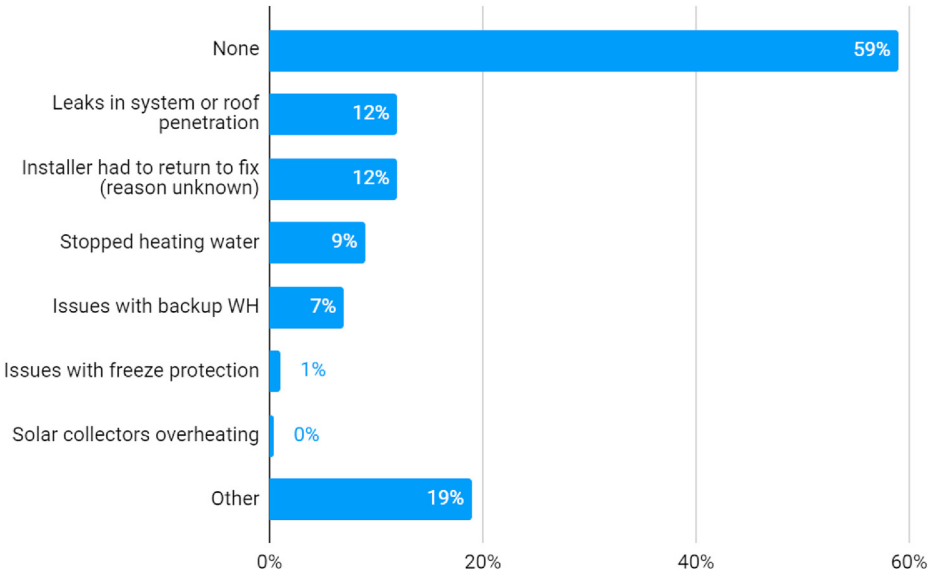

Fig. 7. "Have you had any of the following problems with your solar water heater?".

aspects of their SWH (Fig. 8) and their favorite and least favorite aspects (Figs. 9 and 10). Respondents' top favorite things were: (1) lower energy bills, (2) renewable energy, and (3) better for the environment. Respondents ranked their least favorite aspects as: (1) installation cost, (2) less saving than expected, and (3) takes up too much space.

Most participants reported energy bill savings (Fig. 11) in both summer (69%) and winter (61%), though to a greater degree in summer. It is important to note that self-reported bill savings may often be quite impressionistic since there is no automatic or otherwise simple accounting for these bill savings. Table 3 presents associations (Chi-Square test results) between users' adaptations to SWH and their perceived energy bill savings from reduced natural gas usage. Households that reported changing SWH settings when on vacation and shifting time of hot water usage reported more savings in the summer than those that did not make these adaptations; no relationships were found for winter or changing settings on the backup water heater. It is unclear whether the association found between behavior and energy savings in summer reflect a causal relationship or merely confirmation bias affirming the users' usage strategy.

To measure overall satisfaction with their SWH system, we ask respondents: "On a scale from 0 to 10, 0 being not likely and 10 being extremely likely, how likely are you to recommend SWH to a friend or neighbor?". A similar question was asked about the installer that was used. These questions generated a Net Promoter Score (NPS) for the technology and the installer (each). To assess overall satisfaction across respondents, an aggregate NPS is calculated by grouping the responses into detractors (responses from 0 to 6), passives (7–8), and promoters (9–10), then subtracting the % detractors from the % promoters to get a −100 to 100 score that indicates the distribution of loyalty in the adopting sample. Table 4 compares the results with findings from a survey of 1176 California solar PV adopter households in December 2014 to January 2015, at a time when solar PV was proliferating in California [36]. It appears that in general, solar PV adopters were more satisfied with their

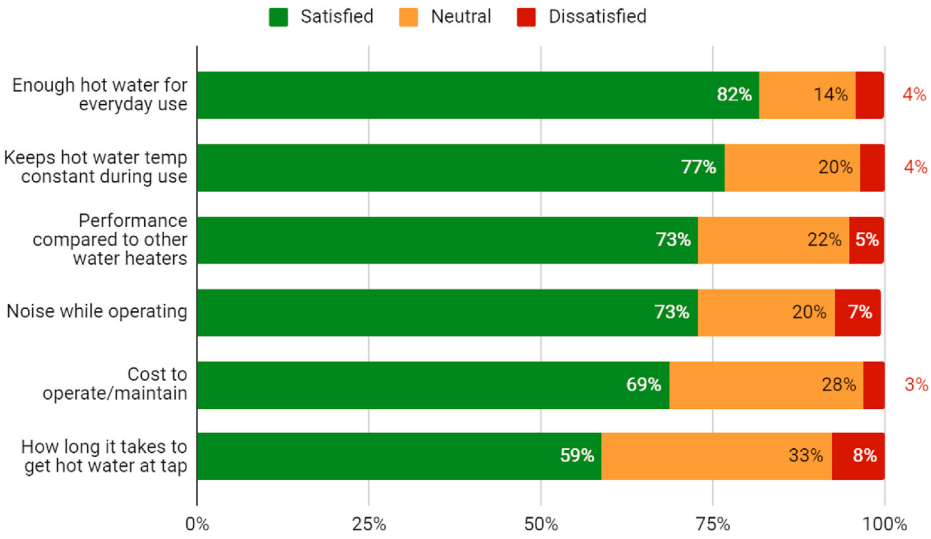

Fig. 8. "Are you satisfied with the following aspects of your SWH?".

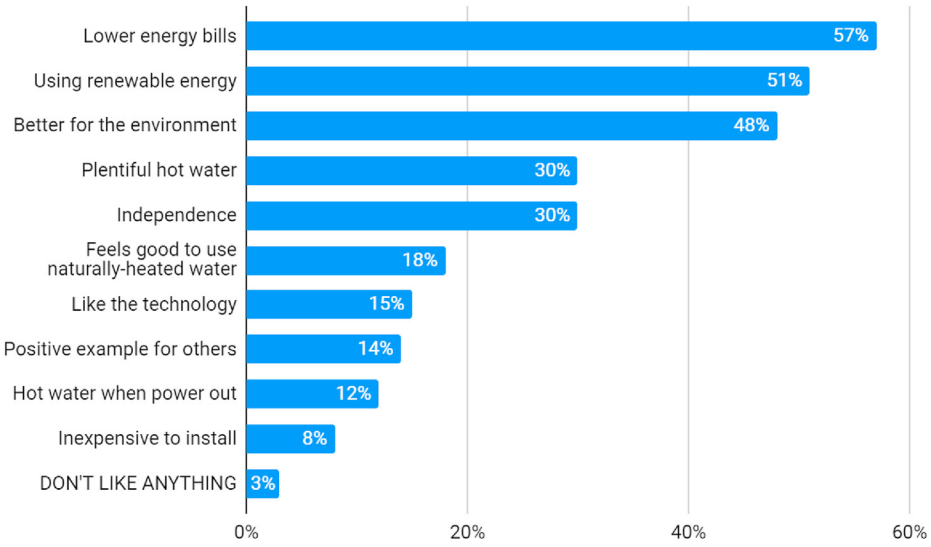

Fig. 9. "What are your three favorite things about your solar water heater?".

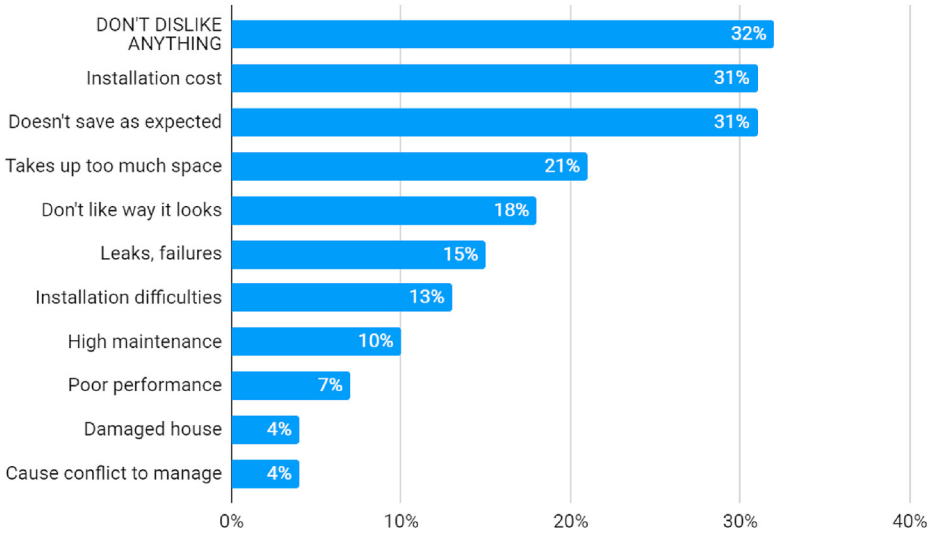

Fig. 10. "What are your three LEAST favorite things about your solar water heater?".

systems than SWH adopters.

The analyses above report the prevalence of various positive and negative assessments of SWH among adopters but do not indicate their relative association with overall satisfaction. For example, participants commonly cited installation cost as a least favorite aspect of SWH, but that does not tell us the degree to which this assessment is related to an overall unfavorable assessment of SWH. Tables 5 and 6 report correlations between individual responses on the general SWH NPS question (0–10, with 10 being extremely likely to recommend SWH to friend or neighbor) and each favorite and least favorite aspect of SWH (binary variables where 1 indicates selection in a respondent's top three favorite or least favorite aspects). The only favorite aspect significantly correlated with NPS rating was "lower energy bills" (positive, minimal magnitude correlation). Several least favorite aspects were significantly negatively correlated with NPS rating, although the magnitudes are also small, with the strongest being "doesn't save as much money/energy as we expected." Both results suggest that the system's ability to save households money was a significant driver of overall satisfaction.

We investigated the potential link between system costs and overall satisfaction. Survey data were triangulated with project incentive and cost information from the CSI-T database by matching participants based on their home address. There was no significant correlation between out-of-pocket SWH costs and SWH NPS ($r = 0.027$, $p = .731$). Note that we do not have verified data on final costs, which was likely zero or near-zero for many households in the SoCalGas utility region due to the contractor strategy to sell a high volume of low cost system configurations. There was also no significant difference in NPS between participants in the single-family incentive program [NPS $M(sd) = 7.6\ (2.8)$] compared to those in the low-income single-family incentive program [NPS $M(sd) = 7.4\ (3.4)$]; $t(215) = 0.44$, $p = .66$. These comparisons were also calculated using individual NPS ratings (1–10) and not the aggregate NPS score of sub-groups.

6. Discussion and conclusions

This research described the experiences of single-family

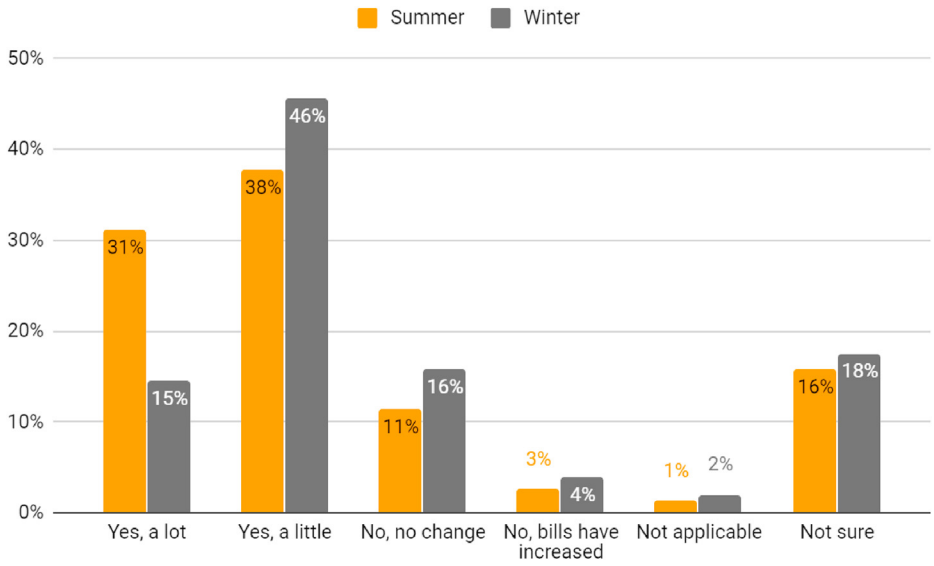

Fig. 11. "On average, have your natural gas bills decreased since getting your SWH?".

Table 3
Relationships between adaptations and reported savings estimates with chi-square test results.

	Change SWH Settings When Away for Long Period		Shift Time of Hot Water Use (Any Activities)		Change Backup WH Settings (Any Circumstances)	
	No or Not Sure ($n = 205$)	Yes ($n = 19$)	No or Not Sure ($n = 185$)	Yes ($n = 37$)	Never ($n = 174$)	Yes ($n = 49$)
Summer Savings	29% Yes, a lot 40% Yes, a little 31% No change, Increase or Not sure ($\chi^2 = 9.5$, $p = .009$)	63% Yes, a lot 21% Yes, a little 16% No change, Increase or Not sure	28% Yes, a lot 40% Yes, a little 32% No change, Increase or Not sure ($\chi^2 = 7.8$, $p = .020$)	51% Yes, a lot 30% Yes, a little 19% No change, Increase or Not sure	30% Yes, a lot 41% Yes, a little 29% No change, Increase or Not sure ($\chi^2 = 1.7$, $p = .418$)	37% Yes, a lot 31% Yes, a little 33% No change, Increase or Not sure
Winter Savings	14% Yes, a lot 47% Yes, a little 39% No change, Increase or Not sure ($\chi^2 = 1.3$, $p = .529$)	22% Yes, a lot 50% Yes, a little 28% No change, Increase or Not sure	14% Yes, a lot 48% Yes, a little 38% No change, Increase or Not sure ($\chi^2 = 0.6$, $p = .751$)	19% Yes, a lot 43% Yes, a little 38% No change, Increase or Not sure	15% Yes, a lot 48% Yes, a little 37% No change, Increase or Not sure ($\chi^2 = .85$, $p = .653$)	15% Yes, a lot 42% Yes, a little 44% No change, Increase or Not sure

Table 4
Net promoter scores for SWH compared to residential photovoltaics.

	SWH ($n = 227$)	PV ($n = 1176$)
General NPS	21	65
Promoters (9–10)	50%	74%
Passives (7–8)	22%	18%
Detractors (0–6)	29%	8%
Installer NPS	14	52
Promoters (9–10)	49%	67%
Passives (7–8)	15%	18%
Detractors (0–6)	35%	15%

Source: Data on PV solar owners from Sigrin et al. [36].

Table 5
Correlations between favorite aspects of SWH and overall SWH NPS.

Aspect	SWH NPS
Lower energy bills	.198[a]
Better for the environment/helps slow climate change	.123
Plentiful hot water	.109
Feels good to use naturally-heated water	.096
Inexpensive to install	.092
Setting a positive example for others in the community	.041
More independence from my energy utility/self-sufficiency	.015
Using renewable energy	-.006
I like the technology	-.061
Hot water when the power goes out	-.106

[a] Correlation is significant at the 0.01 level (2-tailed).

households in California that participated in a state-sponsored incentive program to install SWH and who completed responses to our survey. The intent was to provide a holistic assessment of their experiences and challenges encountered throughout the entire adoption process, using Rogers' five-stages Innovation-Decision process framework [31]. Regarding the Knowledge Stage, the most prevalent communication channels for learning about SWH were word-of-mouth, which suggests that marketing efforts from manufacturers, installers, and utilities have not been particularly salient.

Further challenges for adopters at the Knowledge Stage include a lack of accessible information. Nearly one-third of participants reported that information about SWH was difficult to find. If this substantial proportion of early adopter households finds information difficult to find, it is entirely plausible that non-adopting households lack awareness and easy access to information, too. SWH is not something homeowners will find on their own at retail stores when replacing their standard gas water-heating tank. SWH is also more complicated because it requires a supplemental backup source, and thus, is not a one-to-one replacement technology.

High installation cost was the most prevalent concern for

Table 6
Correlations between least favorite aspects of SWH and overall SWH NPS.

Aspect	SWH NPS
High maintenance	-.114
Costs too much to install	-.102
Takes up too much space	-.078
Don't like the way it looks	-.03
Caused damage to my house	-.006
Installation difficulties	-.006
Causes conflict in home over managing hot water	-.146[b]
Problems such as leaks, component failures	-.170[b]
Poor water-heating performance	-.183[a]
Doesn't save as much money/energy as we expected	-.312[a]

[a] Correlation is significant at the 0.01 level (2-tailed).
[b] Correlation is significant at the 0.05 level (2-tailed).

adopters (36%) in the Persuasion Stage. It also topped the list of least favorite aspects of SWH. These findings suggest that incentives and the cost-effectiveness of installations are important considerations among adopters.

Many households (41%) had difficulties during the installation process (Decision Stage), comparable to the 39% reported in Itron [22]. The most prevalent difficulty was finding a competent and trustworthy installer. Also consistent with Itron's findings, about one in ten adopters had difficulties with permitting and inspection, suggesting these processes have not improved over time.

A significant number of households (41%) experienced problems with their SWH after installation (Implementation Stage); these were mostly different households than the 41% with difficulties during installation. Experiencing performance problems was significantly associated with lower NPS. The overall incidence of performance issues (nearly one in four households reported serious or moderate issues) is concerning. Compounding these known performance issues, it can be difficult for households to determine whether, or to what degree, their SWH is working (e.g., 3% reported they were not sure it was working at all) because the backup (e.g., natural gas-fired or tankless water heater) provides seamless service when the SWH cannot meet demand. As a result, technical problems with the SWH may have been underreported.

While most respondents reported that they thought they had saved energy by installing SWH, nearly one-third said that these savings were less than expected, and this was the SWH drawback most strongly associated with lower NPS, echoing results of previous monitoring studies that found energy savings often fell short of forecasts (reviewed in Moezzi et al. [11]). Setting realistic expectations is challenging because it depends on many dynamic factors (e.g., weather, volume, and timing of hot water consumption) and difficult to observe (e.g., thermal efficiency, installation quality). It is unclear whether adopters were informed of these intricacies.

Reported bill savings were higher among households that reported shifting time of hot water use and changing the SWH settings when away, which only 16% and 8%, respectively, did. It is unclear whether these behaviors yielded the energy savings reported and whether perceived savings were real and attributable to the SWH system, or suggest a biased point of view to justify the effort of active management. Estimating savings is challenging since household bills do not disaggregate natural gas use by end-use (e.g., water heating versus space heating). Priorities undoubtedly varied across households and even among members within households, as evidenced by the fact that SWH caused conflict in some. Previous studies have shown that reducing energy consumption is difficult to achieve when it requires coordination, but the values and behaviors of individuals within a household are at odds [37].

The most recent wave of single-family SWH adopters in California, motivated by energy and associated cost savings and environmental concern, and triggered by incentive availability, are generally satisfied with their systems. However, 29% of respondents' Net Promoter Scores fell in the "detractor" range, suggesting they are not particularly satisfied with their systems and would likely discourage others from installing them. Findings suggest this was due to overall disappointment in the lower-than-expected energy and bill savings, and to a lesser extent the unacceptable rate of severe technical issues with SWH systems.

6.1. Limitations

Studying participants in the CSI-T program allowed a focus on the most recent wave of SWH adoption in California, but it limits the generalizability of findings. This research focused exclusively on single-family households with natural gas backup water heaters, thus results have limited generalizability to households with electric water heating and to multifamily and commercial adopters, who represent a significant proportion of the total potential for energy and cost savings and emissions reductions associated with SWH [7]. Furthermore, due to participation bias associated with voluntary surveys, our sample is not necessarily representative of the population of CSI-T single-family household participants. The exclusive focus on adopters without built-in comparison to non-adopters or considerers further constrains the findings regarding barriers to adoption since all the participants were able to overcome barriers in the earlier stages of adoption. For example, the study showed that finding a SWH installer was challenging, but it does not capture the experience of prospective adopters who never found an installer.

6.2. Future research

Future studies should tie together objective measurement of energy and hot water usage with SWH adopters' subjective experiences. Engaging with installers to understand how they orient adopters to their new SWH systems would also be illuminating. These approaches could help explain whether disappointment in energy savings is due to technical problems or inflated savings projections stemming from inaccurate assumptions about household behavior.

Another promising avenue of inquiry is to consider the pathways of adoption of multiple related technologies (e.g., solar PV and SWH) more carefully. Nearly half the SWH adopters in this study also had rooftop PV, higher than the 38% of adopters in the pilot program, suggesting an increased and successful effort to market SWH to PV owners or otherwise leverage the PV market [20]. A better understanding of the nuanced relationships between PV and SWH adoption—how requirements for each facilitate or constrain opportunities for the other, and issues related to which comes first—could be informative.

6.3. Practical implications

Utilities might consider providing more information and support to customers to help them determine the feasibility and appropriateness of SWH for their home, find a competent installer, and understand how to use the system most effectively, monitor performance, and set realistic expectations. Further measurement and verification research is required to support technology development and installer training so that installations are more likely to lead to expected savings. Finally, providing users with a monitoring and feedback system could inform them about how SWH works, enable performance and saving tracking, and reinforce adaptive

measures that increase savings.

Funding

This work was supported by the California Energy Commission [contract number PIR-15-002].

CRediT authorship contribution statement

Angela Sanguinetti: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing - original draft. **Sarah Outcault:** Writing - review & editing, Project administration, Data curation. **Eli Alston-Stepnitz:** Writing - original draft, Visualization. **Mithra Moezzi:** Conceptualization, Resources, Writing - review & editing, Funding acquisition. **Aaron Ingle:** Methodology, Writing - review & editing, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Survey Questions

Stage	Item	Options
Knowledge	When did you first become aware of solar water heaters?	(1) When I moved into my current home (2) Used to live in a house with solar water heating (3) Saw or used while traveling/living in another country (4) Friends, family, or neighbors had one (5) Plumber/contractor told me about them (6) Media (magazine, TV, radio, Internet) (7) Retailer (8) Manufacturer's advertisement (8) Other (please specify)
	Do you think good information about the following aspects of solar water heaters is easy or difficult to find? ● Whether it is right for your home/lifestyle ● Where to get one ● Installation ● Maintenance ● How to use	(1) Easy to find (2) Difficult to find (3) Not sure
	In a few words, why did your household decide to install a solar water heater?	Open-ended.
	What type of water heating system was in your home prior to the solar water heater?	(1) Standard Tank (2) Whole-house tankless (on-demand) (3) High-efficiency condensing (with plastic vent pipe) (4) High- efficiency condensing (with plastic vent pipe) (5) Electric heat pump (hybrid) water heater (6) Electric heat pump (hybrid) water heater (7) Electric heat pump (hybrid) water heater
Persuasion	Whichof the following influenced you to install solar water heating? (Choose all that apply)	(1) Someone we know (2) Previous water heater failing/broken (3) Low-money-down options (4) Planning/doing other work on home (5) Saw it on/being installed on home (6) Advertising or news article (7) Offered at a retail store, home show, or community event (8) Approached by installer/salesperson (9) Attracted to idea of solar energy source (10) Wanted to save on energy bills (11) Rebate available (12) Building or buying a new home (13) Contractor recommended (14) Dissatisfied with old system's performance/Possibility of more hot water (15) Planning/considering rooftop photovoltaic (PV) (16) Other
	What concerns, if any, did you have when deciding to install a solar water heater? (Choose all that apply)	(1) Concerns about performance (i.e., getting hot enough, or enough hot water) (2) Different solar water heater (3) Risk of leaks or damaging house/roof (4) Having to perform regular maintenance on the system (5) Lack of information (6) Not everyone in your household being convinced (7) That it might be harder to sell your home with solar water heating (8)Unusual technology (9) Concerns about reliability over time (10) That the system might detract from your home's "curb appeal" (11) High initial cost (12) Whether it was a good financial decision (return-on-investment) (13) Other (please specify) (14) None
	How did you get your solar water heating system?	(1) We hired someone to install it (2) It was already installed before we purchased the home/moved in (3) Property owner installed it after we moved in (4) Installed it ourselves
Decision (Installation & Rebate)	As far as financial incentives, rebates, or assistance for your solar water heater, did you (Choose all that apply):	(1) Receive a rebate from your energy utility or California Solar Initiative (CSI) program (2) Take, or plan to take, federal income tax credit (renewable energy) (3) Take out a HERO loan or other PACE Financing (paid back on property taxes) (4) Lease the system from a third party (e.g., City, installing company) (5) Get another rebate, tax credit, financing, or loan (please specify) (6) None of the above
	Do you think you would have installed a solar water heater if the rebate had not been available?	(1) Yes (2) No (3) Maybe, depending on (please specify)
	Were there any difficulties when going through the rebate process (e.g., delays, permitting, design approval, etc.)?	(1) Yes (2) No
	What were the difficulties?	Open-ended.
	What, if any, difficulties did you have during the installation of your solar water heater? (Choose all that apply)	(1) Finding a trustworthy and competent installer (2) Permitting, zoning, inspection, or neighborhood restrictions (please specify) (3) Suitability of your home site (space, shading, orientation, roof structure or condition) (please specify) (4) Damage to something else during installation (please specify) (5) Other (please specify)

(*continued*)

Stage	Item	Options
	Knowing what you do now, do you think you would have done something differently in installing your solar water heater? (Choose all that apply)	(1) Yes, a different type or configuration of a solar water heater (2) Yes, a different contractor/installer (3) Yes, I would not have installed a solar water heater (4) No (5) Don't know
	On a scale of 0–10, how likely are you to recommend your solar water heater installer to a friend or neighbor?	0 = (Not at all likely), 10 =(Extremely likely)
	How did you learn how to use and manage your solar water heating system?	(1) contractor (2) experimenting (3) user's manual (4)other published information (e.g., internet) (5) Talked with other users (6) Other
	What is the condition of your household solar water heating system?	(1) It is working (2) It has been removed (3) It is still there but has been disconnected/is broken (4) Not sure if it is working (5) Other
	As a result of having a solar water heating system (instead of just a conventional water heater), would you say that your household:	(1) Uses MORE hot water (2) Uses LESS hot water (3) Uses about the SAME amount of hot water (4) Don't know (5) Not applicable
	What are the main reasons for using LESS hot water as a result of your solar water heater? (Check all that apply)	(1) There is less hot water produced since we got the solar water heater (2) We try to avoid using the backup water heater (3) We are more aware of how much hot water we use (4) Other reasons (please specify)
Implementation (Use, Maintenance & Repairs)	What are the main reasons for using MORE hot water as a result of your solar water heater? (Check all that apply)	(1) Hot water costs less (2) There is more hot water produced since we got the solar water heater (3) It feels less wasteful knowing that the sun is providing the hot water (4) Other reasons (please specify)
	Have any of the following factors affected your household hot water usage in the past several years? (Check all that apply)	(1) We decreased water use because of concern for the drought (2) Water use has increased because there are more people in the house (3) Water use has decreased because there are fewer people in the house (4) Water costs more now, so we use less (5) Other changes to lifestyles, habits, appliances, or fixtures (please specify) (6) None of the above
	How if at all, has solar water heating affected your household's showering/bathing routines? (Check all that apply)	(1) We take more baths (2) We take fewer baths (3) We take more showers (4) We take fewer showers (5) We take longer showers (6) We take shorter showers (7) No change (8) Not sure (9) Other (please specify)
	How, if at all, has solar water heating affected your household's dishwashing routines? (Check all that apply)	(1) We do more dishwashing loads (2) We do fewer dishwashing loads (3) We hand wash dishes more often (4) We hand wash dishes less often (5) No change (6) Not sure (7) Other (please specify)
	Has your household changed when you use hot water (e.g., changing based on the season or time of day) to adjust to having your solar water heater?	(1) Yes (please describe) (2) No (3) Not sure
	During long periods when nobody is at home (e.g., a long vacation), do you adjust anything about your solar water heating system (e.g., to avoid overheating)?	(1) Yes (please describe) (2) No (3) Not sure
	What is the temperature setting on your backup water heater? Please specify the exact temp if you know it; otherwise indicate a range (Medium is the standard factory setting)	(1) Low (below 130 °F) (2) Medium (130 °F–150 °F) (3) High (over 150 °F) (4) Don't have or use a backup water heater (5) Don't know
	When, if ever, do you change the settings on your backup water heater? (Check all that apply)	(1) Never change it (2) Turn off when on vacation (3) Turn down when on vacation (4) Turn off in summer (5) Turn down in summer (6) Turn up when there are additional people in the home (7) Other (please describe)
	Has your household done anything else to adjust to having the solar water heater?	(1) Yes (please describe) (2) No (3) Not sure
	Have you had any of the following problems with your solar water heater?(Check all that apply)	(1) Issues with freeze protection (2) Issues with backup hot water system (3) Solar collectors overheating (4) Leaks in system or related to roof penetration (5) Stopped heating water (6) Not sure, but the installer had to come back one or more times to fix (7) Other (please specify) (8) None
	How serious do you consider these problems?	(1) Minor (2) Moderate (3) Serious (4) Don't know
	When did the problem first occur?	(1) Within six months after installation (2) Between 6 months and 2 years after installation (3) Between 2 and 5 years after installation (4) More than 5 years after installation (6) Don't know
	About how much in total do you think you have paid for all repairs(not including regular maintenance)?	(1) Less than $100 (2) $100-$499 (3) $500-$999 (4) More than $1000 (5) Have not repaired
	Were the repairs covered under warranty?	(1) Yes, all (2) Yes, some but not all (3) None
	How satisfied are/were you with the warranty?	(1) Extremely satisfied (2) Somewhat satisfied (3) Neither satisfied nor dissatisfied (4) Somewhat dissatisfied (5) Extremely dissatisfied (6) Did not have a warranty
	Whichof the following maintenance measures have you done, or had somebody else do, for your solar water heating system? (Check all that apply)	(1) Inspecting system (2) Washing collectors (3) Flushing and replacing antifreeze/glycol (4) De-scaling (if you have hard water) (5) Regular maintenance service by contractor (6) Other (please specify) (7) Not sure (8) None of the above
	Who has done the maintenance work? (Check all that apply)	(1) Installer (2) Other contractor (3) I/we do (4) No maintenance work has been done yet
	Are you satisfied with the availability of contractors to provide maintenance and repairs?	(1) Yes (optional comment) (2) No (optional comment) (3) Not applicable/ Not sure (optional comment)
	How easy or difficult is it to maintain your solar water heating system?	(1) Extremely easy (2) Somewhat easy (3) Neither easy nor difficult (4) Somewhat difficult (5) Extremely difficult (6) Too soon to tell
	Are you satisfied with the following aspects of your solar water heater? ● Performance compared to other water heaters ● Enough hot water for everyday use ● How long it takes to get hot water at the tap	(1) satisfied (2) neutral (3) dissatisfied
Confirmation	● Keeps hot water temperature constant during use	

(*continued on next page*)

(*continued*)

Stage	Item	Options
	● Noise while operating ● Cost to operate/maintain	
	On average during the **summer**, have your natural gas bills decreased since getting your solar water heater?	(1) Yes, a lot (2) Yes, a little (3) No, no change (4) No, bills have increased (5) Not applicable (6) Not sure
	On average during the **winter**, have your natural gas bills decreased since getting your solar water heater?	(1) Yes, a lot (2) Yes, a little (3) No, no change (4) No, bills have increased (5) Not applicable (6) Not sure
	What are your **three** favorite things about your solar water heater? (Please select up to three)	(1) Hot water when the power goes out (2) Lower energy bills (3) I like the technology (4) Inexpensive to install (5) Using renewable energy (6) Plentiful hot water (7) More independence from my energy utility/self-sufficiency (8) Better for the environment/helps slow climate change (9) Feels good to use naturally-heated water (10) Setting a positive example for others in the community (11) Other (please specify) (12) I don't like anything about it
	What are your **three** least favorite things about your solar water heater? (Please select up to three)	(1) Installation difficulties (2) Problems such as leaks, component failures (3) Takes up too much space (4) Don't like the way it looks (5) Poor water-heating performance (6) Costs too much to install (7) Causes conflict in home over managing hot water (8) Doesn't save as much money/energy as we expected (9) High maintenance (10) Caused damage to my house (11) Other (please specify) (12) I don't dislike anything about it
	How often have you talked about your solar water heater with your neighbors, friends, family, or colleagues?	(1) Never (2) Rarely (3) Sometimes (4) Often
	How likely are you to recommend solar water heating to a friend or neighbor?	0 = (Not at all likely), 10 =(Extremely likely)

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