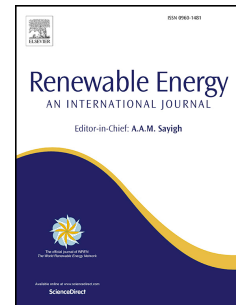


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Residential solar water heaters in Brisbane, Australia: key performance parameters and indicators

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Abstract

A multi-parametric sensitivity analysis of Solar Water Heater (SWH) systems was undertaken for the city of Brisbane in Australia using computational models calibrated by experimental data. The models were calculated using EnergyPlus 8.6. The following technical specification parameters were assessed in the modelling: (i) solar collector efficiency; (ii) solar collector area; (iii) tank volume; (iv) tank heat loss; (v) electric back-up heating power rate; (vi) electric back-up heating position (height) for vertical tanks; and (vii) electric back-up heating temperature range. The site-specific parameters included: (i) solar collector direction; (ii) solar collector tilt angle; (iii) solar collector shadowing; (iv) solar collector dust accumulation; (v) hot water pipe insulation; (vi) hot water pipe length; (vii) electricity tariff time-of-use; and (viii) cold water temperature. User behaviour patterns were comprised of the following parameters: (i) end-use water temperature; (ii) end-use water demand; and (iii) end-use time-of-use. For all parameters, two system types were assessed, namely: (i) thermosiphon systems with natural (passive) circulation in collectors and unstratified horizontal hot water storage tanks; and (ii) split systems with forced (pumped) circulation in collectors and stratified vertical hot water storage tanks. The performance of SWHs was analysed considering both energy performance indicators (i.e. total and peak-hour energy consumption, solar fraction and energy intensity) and level of service indicators (i.e. compliance with recommended hot water temperatures for *Legionella spp.* control and comfort levels). Notwithstanding the prevalence of thermosiphon systems among SWH technologies, results indicate that split systems usually outperformed thermosiphon systems both in terms of energy efficiency and level of service, and hence should be a preferred option for energy efficiency initiatives and policies.

Keywords: solar water heater; sensitivity analysis; site-specific variables; technical specifications; energy performance; level of service.

Nomenclature

CV	Coefficient of variation
CWT	Cold water temperature
EHP	Electric back-up heating position
EHT	Electric back-up heating temperature range
EPR	Electric back-up heating power rate

ETD	Electricity tariff time-of-use
EWD	End-use water demand
EWT	End-use water temperature
EWU	End-use water time-of-use
GHG	Greenhouse Gas
HPI	Hot water pipe insulation
HPL	Hot water pipe length
IoT	Internet of Things
LE	Lower-extreme energy efficiency class
LS	Lower-standard energy efficiency class
p	Null-hypothesis probability (similarity)
R ²	Coefficient of determination
RET	Renewable Energy Target
S	Standard energy efficiency class
SCA	Solar collector area
SCDi	Solar collector direction
SCDu	Solar collector dust accumulation
SCE	Solar collector efficiency
SCS	Solar collector shadowing
SCT	Solar collector tilt angle
SWH	Solar Water Heater
TKI	Tank heat loss
TKV	Tank volume
TLR6	Toll-like receptor 6
UE	Upper-extreme energy efficiency class
US	Upper-standard energy efficiency class

39

40 1. Introduction

41 Australia has one of the largest greenhouse gas (GHG) footprints among developed countries in the world due to its
 42 considerable reliance on fossil fuels for energy supply [1–3]. However, the country receives one of the greatest
 43 quantities of solar radiation on earth, i.e. 1.5–1.9 MWh·m⁻²·year⁻¹ on average [4]. As a result, the use of solar energy
 44 technologies has increased considerably (e.g. 7.2% per annum from 2000 to 2008) in Australia in the last two decades in
 45 connection with the sanction of national policies on GHG emissions mitigation since 1997 [5]. These measures were
 46 usually implemented as part of government renewable energy rebate policies, e.g. Small-Scale Renewable Energy
 47 Scheme [3]. To date, the aim of such policies is to achieve at least 20% of electricity supply from renewable energy
 48 sources by 2020 as part of the Renewable Energy Target (RET) set by the Australian Federal Government, i.e. 33 TWh
 49 per year by 2020 [6,7].

50 Solar water heater (SWH) technologies were among the main strategies endorsed by renewable energy rebate schemes
 51 funded by the Australian government in the past decades. Since the 1950s, this technology has been researched and
 52 developed by Australian research and commercial institutions [8]. Notwithstanding developments in SWH technologies
 53 in the country, the proportion of the residential building stock with SWHs is approximately 5% in Australia [3,4].
 54 Traditionally, the most popular system is flat plate thermosiphon SWHs [4], but there has been an increase in the use of
 55 split SWHs.

In spite of general benefits associated with the use of SWHs in residences in Australia, the performance and electricity savings promoted by these systems is considerably influenced by the characteristics of their components, site-specific conditions and user behaviour. Therefore, SWHs may present inherent cost and efficiency limitations [2]. While cost limitations associated with SWHs for Australian households may be overcome with government renewable energy rebate schemes, efficiency limitations may persist if a careful selection of SWHs is not undertaken. As discussed by Mills [9], the performance of SWHs must be determined by using detailed models, rather than general approaches as the one defined by the Australian Standard AS 4234 – Heated water systems, calculation of energy consumption [10].

The assessment of SWHs must encompass a holistic approach based on multi-parametric analyses and associations between energy performance and service level indicators. Seldom are SWHs assessed considering a large range of variables and indicators under a single assessment framework. Nonetheless, recent studies on SWHs have addressed important aspects related to assessment frameworks, technological advancements, site-specific conditions, and user behaviour patterns. For instance, Allouhi et al. [11] indicated the importance of more efficient systems to reduce the reliance on energy from the electricity grid; Duomarco [12] pointed out the benefits of systems with high solar fractions; Halaway [13] alerted to the necessity of reviewing periodically the input assumption used to estimate the performance of SWHs, e.g. the standard AS/ANZ 4234:2008 on energy consumption modelling; Li et al. [14] showed that the application of vertical solar collectors are equally influenced by site specific conditions, e.g. water consumption pattern and seasonal solar radiation; Yan et al. [15] demonstrated that considerable amounts of energy are missed due to a mismatch of solar collector energy supply and heating demand loads; Saravanan et al. [16] described the connection between technological advancements and performance improvements in the design of solar collectors; Tanha et al. [17] found that performance of systems is usually lower than the one described by manufacturers; Xue [18] studied the performance of new phase change materials for SWHs, which were significantly influenced by site conditions, e.g. cold water temperature and solar radiation variability; Lamnatou et al. [19] identified a lack of studies on the configuration of solar systems for building integrated design; Li et al. [20] investigated the impact of urban forms on the performance of solar systems, revealing a lower influence of site conditions (e.g. site coverage, building azimuths, etc.) on the performance of systems installed in low- and medium-density areas as opposed to high-density areas; Edwards et al. [21] suggested the use of variable water consumption loads based on empirical data, rather than static daily water consumption profiles, for performance assessment models of SWHs; Gill et al. [22] details in a qualitative analysis the interdependence among households, technologies and policies on SWHs, e.g. failure to achieve policy goals (household carbon emission reduction) and benefits for households (energy savings) due to a lack of quality professional advice and installation of systems; Lin et al. [23] assessed the financial feasibility of SWHs, which was dependent upon the daily water consumption pattern; and so on.

Notwithstanding the vast number of studies on SWHs, there is a dearth of studies that comprehensively integrates various technical specification parameters, site-specific conditions, and user behaviour aspects in order to holistically evaluate the performance of SWHs across multiple key performance indicators. The objective of the herein study is to assess the performance of SWHs for the city of Brisbane in Australia using a multi-parametric sensitivity analysis for technical specifications, site-specific conditions and user behaviour variables taking into account energy performance and service level indicators. The analysis was carried out considering the variability of 19 parameters and six performance indicators.

2. Research method

This section provides an overview of the research method undertaken in this study. The study encompasses an analysis of SWHs focused on energy performance indicators (i.e. annual energy consumption, energy intensity, solar fraction and peak energy consumption) and level of service indicators (i.e. compliance with required hot water temperatures for

Legionella spp. control and comfort levels). In order to accomplish the aim of the study, SWHs were assessed for the climate of the city of Brisbane considering 19 parameters combined into 192 scenarios emulated using calibrated computational models. Models were undertaken using the software EnergyPlus 8.6. The result of models were employed to analyse the influence of different technical specifications, site-specific conditions and user behaviour parameters on the six performance indicators of SWHs. Fig. 1 summarises the study method.

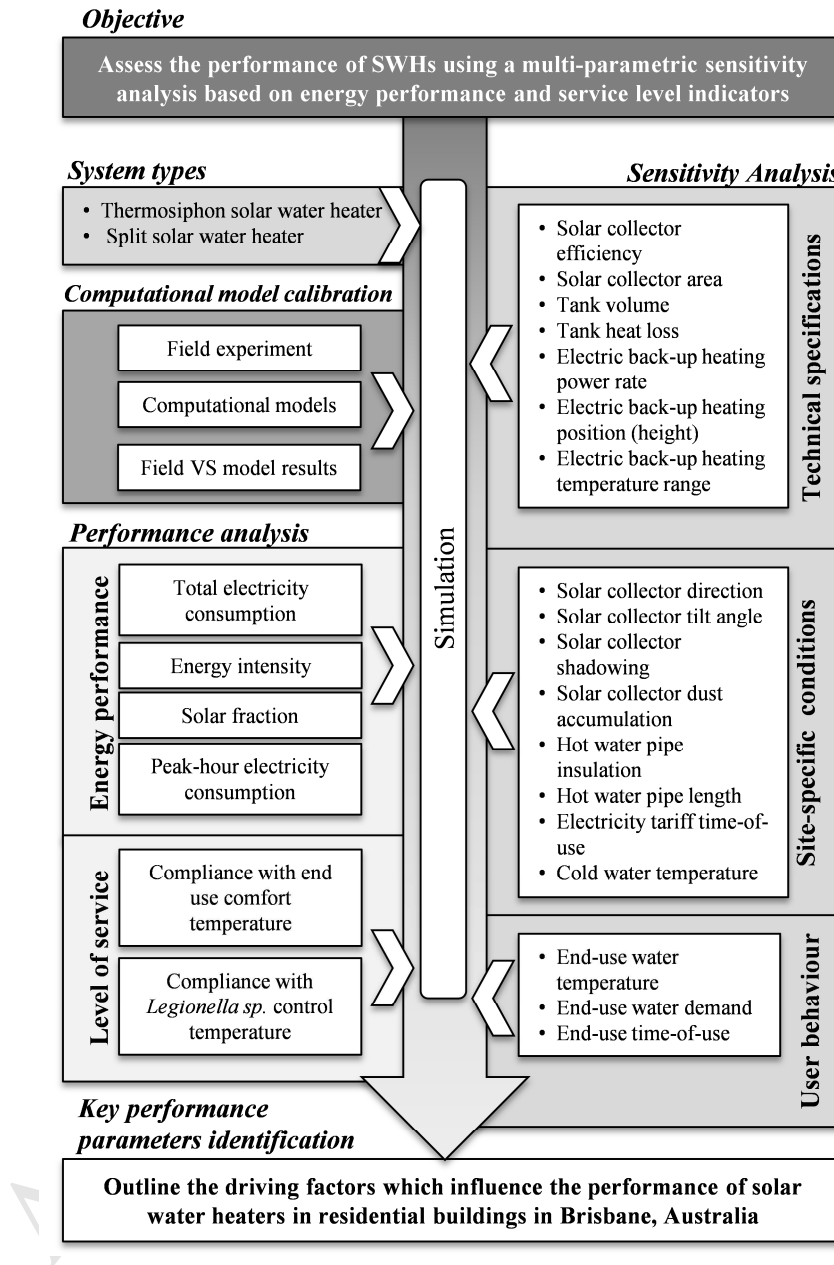


Fig. 1. Flow chart of the study method.

In the supplementary material, a detailed explanation on supporting analyses is provided, including: (i) computational model calibration using a field experiment conducted in Brisbane, Australia (S-A); and (ii) review of input parameters for the sensitivity analysis (S-B).

2.1. Sensitivity analysis inputs

A sensitivity analysis was undertaken to evaluate the performance of split SWHs with vertical stratified tanks and thermosiphon SWHs with horizontal mixed tanks. Electricity was required during auxiliary heating events in split and thermosiphon systems alike, and for operating the pump of the circulation system between solar collectors and the tank in split systems only. In the analysis, three input categories were taken into account, namely: (i) technical specifications; (ii) site-specific conditions; and (iii) user behaviour.

The value range for most of the input parameters was based on five energy efficiency classes, i.e. lower-extreme (LE), lower-standard (LS), standard (S), upper-standard (US) and upper-extreme (UE). The variability of such values was statistically determined for stochastic parameters, whereas prior studies and expert appraisal were adopted for non-stochastic parameters range estimation (refer to Supplementary material S-B for more details). The performance analysis was undertaken considering the variation of values for single parameters at a time, while the other parameters were kept constant at the reference category. The reference category was fixed at the S class, except for the following parameters in accordance with the local solar market practices: solar collector efficiency at LS, solar collector direction at UE, solar collector tilt angle at UE, solar collector shadowing direction at UE, and tariff power interruption at LE. Therefore, the 19 parameters were combined into 192 scenarios by emulating eight directions for two parameters (solar collector orientation and shadowing, $n=16$) and five values for other 16 parameters ($n=80$), with a total of 96 scenarios for two system types (split and thermosiphon systems, $n=192$).

2.2. Key performance indicators

Each studied parameter was analysed considering performance indicators related to energy efficiency and level of service under a single framework. This approach provides a holistic analysis of SWHs, as conservative service levels may lead to excessive electricity consumption, whereas low energy consumption may be associated with reduced service levels.

Energy efficiency indicators encompassed the electricity consumption of auxiliary heating elements of SWHs, including the total annual electricity consumption as well as the peak-hour electricity consumption for the energy grid (i.e. from 4 pm to 8 pm). The total electricity consumption of SWHs was calculated by totalising the electric energy consumption of simulation scenarios for one year. The peak-hour electricity consumption was calculated in an analogous way to the total electricity consumption, but considering peak-hours only.

The solar fraction of SWHs was also used as an indicator. It was calculated as the quotient of the amount of solar energy to the total energy consumption of SWHs (i.e. solar energy and electricity). The consumed solar energy was calculated as a function of the subtraction between the total energy consumption and the electricity requirements of SWHs. Moreover, energy efficiency indicators also included electric energy intensity (unit of energy per unit of water consumption).

Service indicators were related to compliance levels with temperature thresholds for comfort level of users at end-use points and protection against *Legionella spp.* growth in hot water tanks. The compliance level with the end-use point temperatures was analysed by comparing the supplied water temperature with their set-point temperature. The required criteria for *Legionella spp.* control was adopted based on a continuous supply temperature at the storage tank outlet (top hot water layer) of 60 °C as suggested by Bédard et al. [24] and Boppe et al. [25] among other current studies published by government agencies (e.g. UK [26]). Notwithstanding the general inhibition of *Legionella spp.* for temperature equal to 60 °C, such bacteria group may persist under growth-restrictive temperatures (<20 and >55 °C) and heat shocks (70°C for 30 minutes) [27].

The herein assessment of *Legionella spp.* control temperature only provides an indication of the susceptibility of hot water supply systems to *Legionella spp.* growth as described in Table 1. Mercante and Winchell [27] pointed out that the proliferation of *Legionella spp.* in hot water supply systems is not directly associated with clinical cases of legionellosis, as this disease tend to occur when other underlying factors in addition to exposure to aerosols with *Legionella spp.* are present, such as: over 50 years-old man with lung disease, immunosuppression, smoking, recent travel, diabetes, cancer, acquired immune deficiency syndrome, end-stage renal disease, and human cellular Toll-like receptor 6 (TLR6) mutations. The authors also reported that the number of legionellosis has increased in the past decades, which may be attributed to a rise in diagnostic testing techniques, improvements in reporting, and growth of vulnerable elderly population.

Table 1. *Legionella spp.* proliferation risk in hot water supply systems.

Water heater outlet temperature (°C)	Time frequency (%)	Risk
≥ 60	100	Very low
≥ 60	90-99	Low
≥ 60	51-89	Intermediate
≥ 60	0-50	High

Note: Adapted from Bédard et al. [24].

3. Performance analysis

Among the 19 studied parameters, the sensitivity analysis revealed a diversified interaction among the performance of SWHs, both in terms of energy efficiency and level of service, and the variability of technical specifications of SWHs, site specific conditions and user behaviour. As shown in Table 2, the electricity consumption of SWHs underwent a significant variation under different energy efficiency classes for most of the parameters.

Table 2. Absolute and relative change in electricity consumption.

	System type Energy efficiency class	Split with stratified vertical tank					Thermosiphon with mixed horizontal tank				
		LE	LS	S	US	UE	LE	LS	S	US	UE
Solar collector	Efficiency (%)	39	43	56	64	67	39	43	56	64	67
	Electricity use (kWh/year)	416	340	118	107	100	450	365	61	42	32
	Electricity use change (%)	22	0	-65	-68	-71	23	0	-83	-88	-91
	Area (m ²)	1.8	2.8	5.6	9.0	10.4	1.8	2.8	5.6	9.0	10.4
	Electricity use (kWh/year)	1072	749	340	201	176	875	643	365	236	219
	Electricity use change (%)	215	120	0	-41	-48	140	76	0	-36	-40
	Direction/orientation*	S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
	Electricity use (kWh/year)	1099	940	614	397	340	1023	893	662	438	365
	Electricity use change (%)	223	177	80	17	0	180	144	81	20	0
	Tilt angle	90°	0°	13.7°	47.4°	27.4°	90°	0°	13.7°	47.4°	27.4°
	Electricity use (kWh/year)	1314	609	437	381	340	1270	-	489	401	365
	Electricity use change (%)	286	79	29	12	0	248	-	34	10	0
	Shadowing direction*	N	NE/NW	E/W	S/SE/SW	None	N	NE/NW	E/W	S/SE/SW	None
	Electricity use (kWh/year)	586	447	354	347	340	642	509	394	369	365
	Electricity use change (%)	72	31	4	2	0	76	39	8	1	0
Hot water tank	Dust radiation decline (%)	64.0	47.0	5.0	2.7	0.0	64.0	47.0	5.0	2.7	0.0
	Electricity use (kWh/year)	1584	1234	340	312	283	1449	1235	365	332	294
	Electricity use change (%)	366	263	0	-8	-17	297	238	0	-9	-19
	Volume (litres)	90	250	315	450	630	90	250	315	450	630
	Electricity use (kWh/year)	549	372	340	354	385	774	434	365	291	240
	Electricity use change (%)	62	10	0	4	13	112	19	0	-20	-34
	Heat loss (W/K)	3.1	1.3	0.8	0.5	0.2	3.1	1.3	0.8	0.5	0.2
	Electricity use (kWh/year)	1569	605	340	241	165	963	507	365	303	246
	Electricity use change (%)	361	78	0	-29	-51	163	39	0	-17	-33
	Cold water connection (°C)	14-21	16-23	20-27	24-31	26-33	14-21	16-23	20-27	24-31	26-33
	Electricity use (kWh/year)	517	452	340	248	212	636	544	365	213	160
	Electricity use change (%)	52	33	0	-27	-38	74	49	0	-42	-56
	Insulation (R-value)	0.0	0.2	0.3	1.0	AD**	0.0	0.2	0.3	1.0	AD**
	Electricity use (kWh/year)	433	343	340	339	297	406	368	365	362	270

Electricity use change (%)	27	1	0	0	-13	11	1	0	-1	-26
	18	15	9	5	0	18	15	9	5	0
Length (metres)	364	356	340	331	298	411	402	365	326	270
Electricity use (kWh/year)	7	5	0	-3	-12	13	10	0	-11	-26
Electricity use change (%)	5.5	4.8	3.0	1.5	0.9	5.5	4.8	3.0	1.5	0.9
Element power (kW)	325	325	340	348	328	367	367	365	352	334
Electricity use (kWh/year)	-4	-4	0	2	-3	1	0	0	-4	-9
Electricity use change (%)	0	25	50	75	100	-	-	-	-	-
Element tank height (%)	1029	460	340	280	245	-	-	-	-	-
Electricity use (kWh/year)	203	35	0	-18	-28	-	-	-	-	-
Electricity use change (%)	80	74	60	53	50	80	74	60	53	50
Set-point temperature (°C)	1334	965	340	182	143	1195	918	365	173	137
Electricity use (kWh/year)	292	184	0	-47	-58	227	151	0	-53	-62
Electricity use change (%)	0	2	3	6	16	0	2	3	6	16
Tariff power interruption (h)	340	337	337	320	175	365	365	365	321	236
Electricity use (kWh/year)	0	-1	-1	-6	-49	0	0	0	-12	-35
Electricity use change (%)	50	47	40	35	33	50	47	40	35	33
End-use temperature (°C)	571	517	340	239	206	814	664	365	192	129
Electricity use (kWh/year)	68	52	0	-30	-39	123	82	0	-48	-65
Electricity use change (%)	233	210	155	100	77	233	210	155	100	77
Water demand (litres/day)	612	521	340	208	162	815	664	365	138	88
Electricity use (kWh/year)	80	53	0	-39	-52	123	82	0	-62	-76
Electricity use change (%)	6:50	7&17	7:30&18	9&20	9:40	6:50	7&17	7:30&18	9&20	9:40
Time of peak use hour (24h)	350	342	340	291	248	349	364	365	334	300
Electricity use (kWh/year)	3	0	0	-14	-27	-5	0	0	-8	-18
Electricity use change (%)										

Note: * North (N), Northeast (NE), Northwest (NW), East (E), West (W), Southeast (SE), Southwest (SW), South (S); ** Adiabatic (AD)

Under the reference energy efficiency class for each parameter (base scenario), split and thermosiphon SWHs had an electricity consumption of 340 and 365 kWh·year⁻¹ per household, respectively, with an equivalent energy intensity of approximately 6 kWh·m⁻³. The use other energy efficiency classes showed a significant effect on the electricity savings of SWHs. For instance, the replacement of lower-standard collectors (most popular collector category in the local market) with standard performance collectors (median efficiency level among the 135 glazed solar collectors' sample) promoted a decrease in energy intensity of 65% (1 kWh·m⁻³) for split systems and 83% (2 kWh·m⁻³) for thermosiphon systems. Conversely, a 64% transmittance reduction on solar collectors associated with excessive levels of dust accumulation, or other type of dirt (e.g. grime, bird drops, etc.), may almost eliminate the solar energy collection of SWHs. Under such conditions, there exists a tremendous increase in electricity consumption and associated energy intensity to ranges comparable to electric water heaters, i.e. 25 and 28 kWh·m⁻³ for thermosiphon and split SWHs, respectively.

Reductions in the electricity consumption during peak-hours for the energy grid (i.e. from 4 pm to 8 pm) were mainly related to two major SWHs groups, namely: (i) systems with high energy efficiency and low electricity requirements during peak-hours; and (ii) systems with low energy efficiency with a random displacement of electricity consumption from peak-hours. The peak electricity consumption analysis is summarised in Table 3.

Table 3. Absolute and relative change in peak electricity consumption.

System type Energy efficiency class	Split with stratified vertical tank					Thermosiphon with mixed horizontal tank				
	LE	LS	S	US	UE	LE	LS	S	US	UE
Efficiency (%)	39	43	56	64	67	39	43	56	64	67
Peak use (kWh/year)	12	17	6	3	0	72	91	15	8	8
Peak use change (%)	-27	0	-65	-81	-100	-21	0	-83	-92	-92
Area (m²)	1.8	2.8	5.6	9	10.4	1.8	2.8	5.6	9	10.4
Peak use (kWh/year)	32	22	17	10	7	114	109	91	80	79
Peak use change (%)	89	32	0	-41	-59	25	20	0	-12	-14
Direction/orientation*	S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
Peak use (kWh/year)	207	155	25	16	18	49	387	67	58	91
Peak use change (%)	1023	738	36	-15	0	-46	323	-27	-36	0
Tilt angle	90°	0°	13.7°	47.4°	27.4°	90°	0°	13.7°	47.4°	27.4°
Peak use (kWh/year)	162	17	13	15	17	318	-	31	128	91
Peak use change (%)	869	0	-21	-12	0	247	-	-66	40	0
Shadowing direction*	N	NE/NW	E/W	S/SE/SW	None	N	NE/NW	E/W	S/SE/SW	None
Peak use (kWh/year)	32	25	19	18	17	48	93	91	91	91
Peak use change (%)	89	48	13	3	0	-48	1	-1	0	0

	Dust radiation decline (%)	64	47	5	2.7	0	64	47	5	2.7	0
	Peak use (kWh/year)	172	59	18	15	16	6	80	91	82	79
	Peak use change (%)	833	219	0	-16	-13	-93	-13	0	-11	-14
Hot water tank	Volume (litres)	90	250	315	450	630	90	250	315	450	630
	Peak use (kWh/year)	43	28	18	21	41	172	71	91	94	67
	Peak use change (%)	134	54	0	12	122	88	-23	0	2	-27
	Heat loss (W/K)	3.08	1.32	0.75	0.47	0.18	3.08	1.32	0.75	0.47	0.18
	Peak use (kWh/year)	125	36	17	10	5	164	61	91	88	96
	Peak use change (%)	638	113	0	-43	-71	79	-33	0	-4	5
Hot water pipe	Cold water connection (°C)	14-21	16-23	20-27	24-31	26-33	14-21	16-23	20-27	24-31	26-33
	Peak use (kWh/year)	12	15	17	9	7	118	78	91	63	52
	Peak use change (%)	-27	-11	0	-44	-58	29	-15	0	-32	-43
	Insulation (R-value)	0	0.2	0.3	1	AD**	0	0.2	0.3	1	AD**
	Peak use (kWh/year)	29	19	18	18	12	85	92	91	88	90
	Peak use change (%)	56	3	0	-4	-33	-7	0	0	-4	-2
Electrical installation	Length (metres)	18	15	9	5	0	18	15	9	5	0
	Peak use (kWh/year)	15	18	17	17	12	86	68	91	78	89
	Peak use change (%)	-14	5	0	-3	-30	-5	-25	0	-14	-2
	Element power (kW)	5.5	4.8	3	1.5	0.9	5.5	4.8	3	1.5	0.9
	Peak use (kWh/year)	26	27	18	18	19	91	91	91	91	32
	Peak use change (%)	42	44	0	-1	2	0	0	0	-1	-65
User behaviour	Element tank height (%)	0	25	50	75	100	-	-	-	-	-
	Peak use (kWh/year)	381	83	17	6	10	-	-	-	-	-
	Peak use change (%)	2140	387	0	-67	-42	-	-	-	-	-
	Set-point temperature (°C)	80	74	60	53	50	80	74	60	53	50
	Peak use (kWh/year)	67	48	17	11	4	323	248	91	45	25
	Peak use change (%)	292	184	0	-36	-75	253	171	0	-51	-73
User behaviour	Tariff power interruption (h)	0	2	3	6	16	0	2	3	6	16
	Peak use (kWh/year)	17	3	0	0	0	91	1	0	0	0
	Peak use change (%)	0	-84	-100	-100	-100	0	-98	-100	-100	-100
	End-use temperature (°C)	50	47	40	35	33	50	47	40	35	33
	Peak use (kWh/year)	33	21	17	8	3	147	129	91	38	48
	Peak use change (%)	97	28	0	-53	-80	61	42	0	-59	-47
User behaviour	Water demand (litres/day)	233	210	155	100	77	233	210	155	100	77
	Peak use (kWh/year)	33	22	17	5	6	116	109	91	49	28
	Peak use change (%)	95	31	0	-71	-66	27	19	0	-46	-69
	Time of peak use hour (24h)	6:50	7&17	7:30&18	9&20	9:40	6:50	7&17	7:30&18	9&20	9:40
	Peak use (kWh/year)	5	17	17	4	3	0	98	91	3	0
	Peak use change (%)	-71	1	0	-74	-83	-100	7	0	-97	-100

Note: * North (N), Northeast (NE), Northwest (NW), East (E), West (W), Southeast (SE), Southwest (SW), South (S); ** Adiabatic (AD)

The use of high energy performance systems was associated with a significant decrease in peak-hour electricity requirements, e.g. total displacement of electricity from peak-hours by adopting split SWHs with upper-extreme solar collector efficiency. This outcome has a direct benefit for the energy sector, as a reduction in peak-hour electricity consumption usually contributes to a deferral of capital expenditures for upgrades of energy grids. Peak-hour electricity reductions were also achieved by systems with low performance (e.g. thermosiphon SWHs with North shadowing or 64% transmittance reduction due to dust accumulation in collectors). Notwithstanding this apparent benefit, such systems have a limited electricity saving potential and may lead to a considerable increase in the peak-hour energy consumption depending on user behaviour pattern. The use of split SWHs with electric heating element placed at the bottom of hot water tanks showed the largest increase in peak-hour electricity consumption (21-fold) in relation to the base scenario. This system configuration (i.e. heating element and thermostat positioned at the same level as the cold water inlet) operates constantly heating cold water, and hence provides a larger hot water supply capacity by jeopardising the potential of split SWHs to divert electricity consumption from peak-hours.

The solar energy use proportion in relation to the total energy requirement of SWHs (solar fraction) was mainly influenced by factors associated with the characteristics of solar collectors (Table 4); however, other factors related to user behaviour and back-up electricity heating set-point temperature also played an important role in the solar fraction of SWHs.

Table 4. Absolute and relative change in solar energy fraction.

System type		Split with stratified vertical tank					Thermosiphon with mixed horizontal tank				
Energy efficiency class		LE	LS	S	US	UE	LE	LS	S	US	UE
Solar collector	Efficiency (%)	39	43	56	64	67	39	43	56	64	67
	Solar fraction (%)	82	86	97	98	98	71	76	97	98	98
	Solar fraction change (%)	-5	0	13	14	14	-7	0	28	29	29
	Area (m²)	1.8	2.8	5.6	9	10.4	1.8	2.8	5.6	9	10.4
	Solar fraction (%)	45	64	86	93	94	41	57	76	85	86
	Solar fraction change (%)	-48	-26	0	8	9	-46	-25	0	12	13
	Direction/orientation*	S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
	Solar fraction (%)	42	52	71	83	86	31	40	57	72	76
	Solar fraction change (%)	-51	-39	-17	-4	0	-59	-47	-26	-6	0
	Tilt angle	90°	0°	13.7°	47.4°	27.4°	90°	0°	13.7°	47.4°	27.4°
	Solar fraction (%)	29	72	81	83	86	14	-	68	74	76
	Solar fraction change (%)	-67	-17	-6	-3	0	-82	-	-10	-4	0
	Shadowing direction*	N	NE/NW	E/W	S/SE/SW	None	N	NE/NW	E/W	S/SE/SW	None
	Solar fraction (%)	73	79	85	85	86	58	67	74	76	76
Hot water tank	Solar fraction change (%)	-16	-7	-1	0	0	-24	-13	-3	0	0
	Dust radiation decline (%)	64	47	5	2.7	0	64	47	5	2.7	0
	Solar fraction (%)	13	35	86	87	89	1	16	76	79	81
	Solar fraction change (%)	-85	-59	0	2	3	-99	-79	0	3	6
	Volume (litres)	90	250	315	450	630	90	250	315	450	630
	Solar fraction (%)	69	83	86	86	86	50	72	76	81	84
	Solar fraction change (%)	-20	-3	0	1	1	-35	-6	0	6	10
	Heat loss (W/K)	3.08	1.32	0.75	0.47	0.18	3.08	1.32	0.75	0.47	0.18
	Solar fraction (%)	60	78	86	89	92	59	71	76	79	82
	Solar fraction change (%)	-30	-9	0	3	7	-22	-7	0	4	8
	Cold water connection (°C)	14-21	16-23	20-27	24-31	26-33	14-21	16-23	20-27	24-31	26-33
	Solar fraction (%)	81	82	86	89	90	67	70	76	84	87
	Solar fraction change (%)	-6	-4	0	4	5	-12	-9	0	9	13
	Insulation (R-value)	0	0.2	0.3	1	AD**	0	0.2	0.3	1	AD**
Hot water pipe	Solar fraction (%)	83	86	86	86	87	75	76	76	77	81
	Solar fraction change (%)	-4	0	0	0	2	-2	0	0	0	6
	Length (metres)	18	15	9	5	0	18	15	9	5	0
	Solar fraction (%)	85	85	86	86	87	75	75	76	78	81
	Solar fraction change (%)	-1	-1	0	0	1	-1	-1	0	3	7
	Element power (kW)	5.5	4.8	3	1.5	0.9	5.5	4.8	3	1.5	0.9
	Solar fraction (%)	87	87	86	85	86	76	76	76	77	78
	Solar fraction change (%)	1	1	0	0	1	0	0	0	1	3
	Element tank height (%)	0	25	50	75	100	-	-	-	-	-
	Solar fraction (%)	54	80	86	89	90	-	-	-	-	-
	Solar fraction change (%)	-37	-7	0	3	5	-	-	-	-	-
	Set-point temperature (°C)	80	74	60	53	50	80	74	60	53	50
	Solar fraction (%)	42	58	86	94	96	29	44	76	89	91
	Solar fraction change (%)	-51	-33	0	9	12	-62	-42	0	17	20
Electrical installation	Tariff power interruption (h)	0	2	3	6	16	0	2	3	6	16
	Solar fraction (%)	86	86	86	87	94	76	76	76	79	85
	Solar fraction change (%)	0	0	0	1	9	0	0	0	4	11
	End-use temperature (°C)	50	47	40	35	33	50	47	40	35	33
	Solar fraction (%)	79	81	86	89	90	62	66	76	85	89
	Solar fraction change (%)	-7	-6	0	4	5	-19	-13	0	11	16
	Water demand (litres/day)	233	210	155	100	77	233	210	155	100	77
	Solar fraction (%)	78	81	86	91	93	61	66	76	88	91
	Solar fraction change (%)	-9	-6	0	6	8	-20	-14	0	16	20
	Time of peak use hour (24h)	6:50	7&17	7:30&18	9&20	9:40	6:50	7&17	7:30&18	9&20	9:40
	Solar fraction (%)	85	86	86	88	90	77	77	76	78	80
	Solar fraction change (%)	0	0	0	3	5	0	0	0	3	4
	User behaviour										

Note: * North (N), Northeast (NE), Northwest (NW), East (E), West (W), Southeast (SE), Southwest (SW), South (S); ** Adiabatic (AD)

The maximum solar fraction (98%) was reached with the use of solar collectors in the upper extreme energy efficiency class, i.e. solar collectors with a 67% solar energy collection efficiency. Conversely, the use of lower extreme tilt angles (vertical position) and dust accumulation levels (64% transmittance reduction) in solar collectors promoted a considerable decline in the solar fraction of SWHs, with a minimum of 1% for thermosiphon SWHs with 64% dust accumulation. User behaviour also showed a significant influence on the solar fraction of SWHs; for example, lower- and upper-extreme water consumption patterns (77 and 233 litres·day⁻¹, respectively) were associated with an increase

and decrease of 20% in the solar fraction of thermosiphon SWHs in relation to the base scenario. By decreasing the electric heating element set-point temperature from 60 to 50 °C, the solar fraction of thermosiphon SWHs increased by 20%; nonetheless, this practice reduces the compliance level with *Legionella spp.* control temperatures (Table 5).

Table 5. Absolute and relative change in temperature compliance levels for *Legionella spp.* control.

System type	Energy efficiency class	Split with stratified vertical tank					Thermosiphon with mixed horizontal tank				
		LE	LS	S	US	UE	LE	LS	S	US	UE
Solar collector	Efficiency (%)	39	43	56	64	67	39	43	56	64	67
	Compliance (%)	67	72	94	94	95	61	66	95	96	97
	Compliance change (%)	-7	0	31	31	32	-8	0	44	45	47
	Area (m²)	1.8	2.8	5.6	9	10.4	1.8	2.8	5.6	9	10.4
	Compliance (%)	17	41	72	83	85	27	41	66	77	79
	Compliance change (%)	-76	-43	0	15	18	-59	-38	0	17	20
	Direction/orientation*	S	SE/SW	E/W	NE/NW	N	S	SE/SW	E/W	NE/NW	N
	Compliance (%)	28	36	50	67	72	28	33	51	62	66
	Compliance change (%)	-61	-51	-31	-7	0	-57	-50	-22	-6	0
	Tilt angle	90°	0°	13.7°	47.4°	27.4°	90°	0°	13.7°	47.4°	27.4°
	Compliance (%)	9	51	64	66	72	10	-	62	56	66
	Compliance change (%)	-88	-30	-11	-9	0	-85	-	-6	-16	0
	Shadowing direction*	N	NE/NW	E/W	S/SE/SW	None	N	NE/NW	E/W	S/SE/SW	None
	Compliance (%)	49	55	69	72	72	56	55	63	66	66
	Compliance change (%)	-31	-24	-4	0	0	-16	-18	-5	-1	0
Hot water tank	Dust radiation decline (%)	64	47	5	2.7	0	64	47	5	2.7	0
	Compliance (%)	0	7	72	74	76	1	13	66	68	72
	Compliance change (%)	-100	-90	0	3	6	-98	-81	0	3	8
	Volume (litres)	90	250	315	450	630	90	250	315	450	630
	Compliance (%)	69	74	72	67	55	56	67	66	65	62
	Compliance change (%)	-4	3	0	-7	-24	-15	1	0	-2	-6
	Heat loss (W/K)	3.08	1.32	0.75	0.47	0.18	3.08	1.32	0.75	0.47	0.18
	Compliance (%)	32	61	72	78	84	47	61	66	69	72
	Compliance change (%)	-56	-15	0	8	17	-29	-8	0	5	9
	Cold water connection (°C)	14-21	16-23	20-27	24-31	26-33	14-21	16-23	20-27	24-31	26-33
Hot water pipe	Compliance (%)	68	70	72	76	77	59	61	66	72	76
	Compliance change (%)	-6	-3	0	5	7	-11	-8	0	9	14
	Insulation (R-value)	0	0.2	0.3	1	AD**	0	0.2	0.3	1	AD**
	Compliance (%)	68	72	72	72	73	64	66	66	66	70
	Compliance change (%)	-6	0	0	0	2	-4	0	0	-1	5
	Length (metres)	18	15	9	5	0	18	15	9	5	0
	Compliance (%)	72	72	72	73	73	63	65	66	66	69
	Compliance change (%)	0	0	0	1	1	-5	-2	0	0	5
	Element power (kW)	5.5	4.8	3	1.5	0.9	5.5	4.8	3	1.5	0.9
	Compliance (%)	71	72	72	73	72	66	66	66	65	64
Electrical installation	Compliance change (%)	-1	-1	0	1	0	0	0	0	-2	-3
	Element tank height (%)	0	25	50	75	100	-	-	-	-	-
	Compliance (%)	87	74	72	70	69	-	-	-	-	-
	Compliance change (%)	21	3	0	-3	-4	-	-	-	-	-
	Set-point temperature (°C)	80	74	60	53	50	80	74	60	53	50
	Compliance (%)	100	100	72	66	65	100	100	66	55	54
	Compliance change (%)	39	39	0	-8	-10	52	52	0	-17	-18
	Tariff power interruption (h)	0	2	3	6	16	0	2	3	6	16
	Compliance (%)	72	72	72	72	66	66	66	66	64	57
	Compliance change (%)	0	0	0	-1	-9	0	0	0	-4	-14
User behaviour	End-use temperature (°C)	50	47	40	35	33	50	47	40	35	33
	Compliance (%)	65	67	72	77	78	57	59	66	74	77
	Compliance change (%)	-10	-7	0	6	8	-14	-11	0	12	16
	Water demand (litres/day)	233	210	155	100	77	233	210	155	100	77
	Compliance (%)	65	67	72	78	80	59	60	66	76	82
	Compliance change (%)	-10	-7	0	8	11	-11	-9	0	15	24
	Time of peak use hour (24h)	6:50	7&17	7:30&18	9&20	9:40	6:50	7&17	7:30&18	9&20	9:40
	Compliance (%)	73	72	72	71	69	80	65	66	66	79
	Compliance change (%)	1	-1	0	-1	-4	21	-2	0	0	20

Note: * North (N), Northeast (NE), Northwest (NW), East (E), West (W), Southeast (SE), Southwest (SW), South (S); ** Adiabatic (AD)

The compliance levels with the *Legionella spp.* control temperature (60 °C) at the storage tank outlet (top hot water layer) was mainly influenced by the electric heating element set-point temperature. A decrease of this parameter from 60 to 50 °C showed a reduction of 10% and 18% in compliance levels of split and thermosiphon SWHs, respectively;

whereas, the increase of this parameter to 74 °C promoted the full compliance of all SWHs with control temperatures. Despite the inhibition of *Legionella spp.* for temperatures equal or over 60 °C, such bacteria group may persist after heat shocks (70°C for 30 minutes).

Results indicate that the characteristics and conditions of solar collectors are critical to achieve low electricity consumption at high compliance levels with *Legionella spp.* control temperatures. For instance, the use of collectors from the upper-extreme efficiency class showed compliance levels of 95% and 97% for split and thermosiphon SWHs, respectively. Conversely, lower-extreme efficiency levels for dust accumulation (64%) and position (vertical) of solar collectors showed the poorest levels of compliance with control temperatures, i.e.0-1% and 9-10%, respectively.

The comparison among the different parameter groups (i.e. technical specifications, site specific conditions, and user behaviour) showed no significant variation for the total annual electricity consumption (null-hypothesis probability (p) >0.70), solar fraction (p >0.25), peak-hour electricity consumption (p >0.90), and *Legionella spp.* control temperature compliance (p >0.25). The energy intensity was not tested as it is a direct function of the annual electricity consumption; while, results for the end-use temperature were not compared due to the full compliance of studied scenarios with this indicator. Fig. 2 illustrates the Coefficient of Variation (CV) of assessed parameters for key performance indicators.

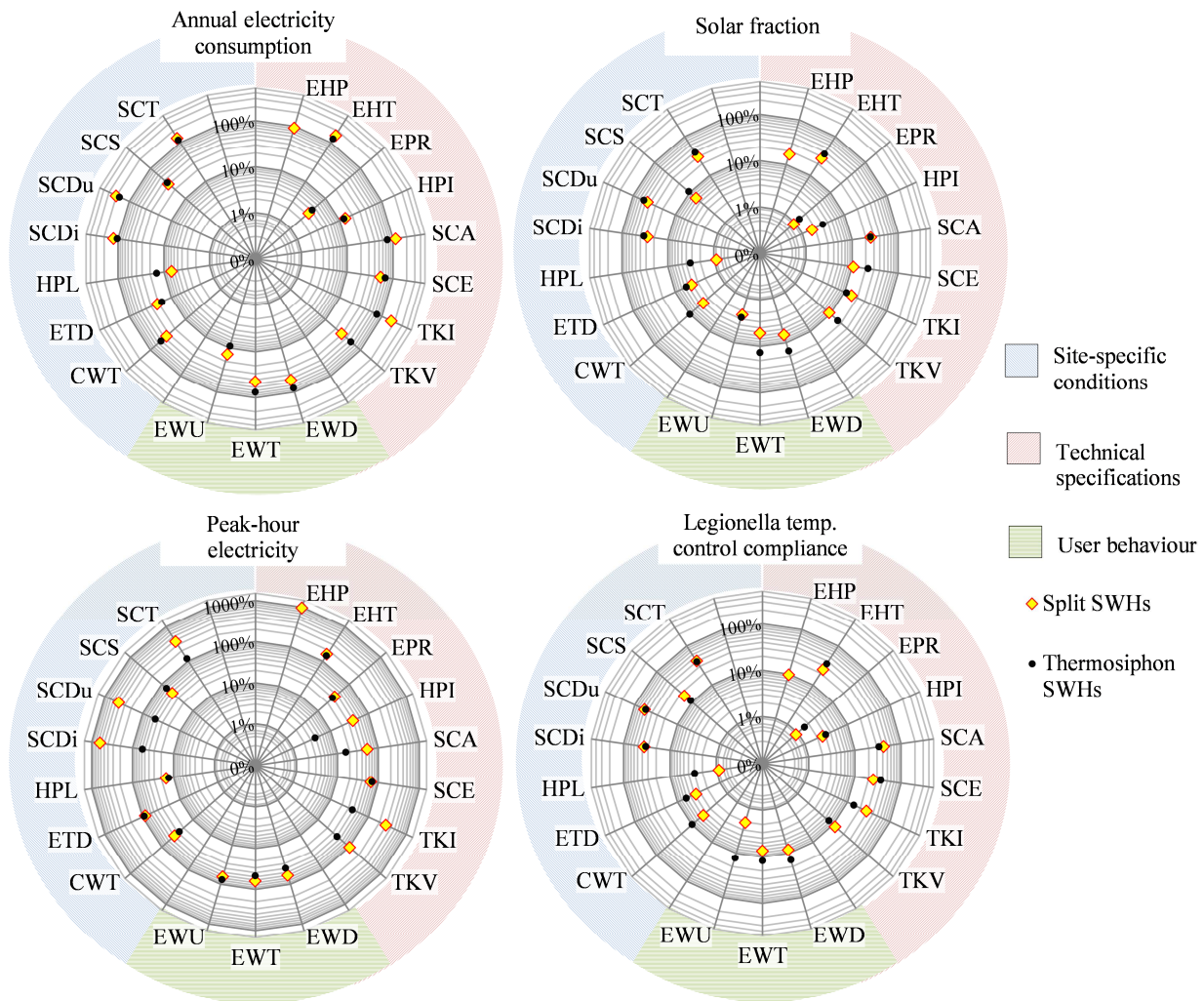


Fig. 2. Coefficient of variation of energy performance and service of level indicators.

Note: Solar water heaters (SWHs), Electric back-up heating position (EHP), Electric back-up heating temperature range (EHT), Electric back-up heating power rate (EPR), Hot water pipe insulation (HPI), Solar collector area (SCA), Solar collector efficiency

(SCE), Tank heat loss (TKI), Tank volume (TKV), End-use water demand (EWD), End-use water temperature (EWT), End-use water time-of-use (EWU), Cold water temperature (CWT), Electricity tariff time-of-use (ETD), Hot water pipe length (HPL), Solar collector direction (SCDi), Solar collector dust accumulation (SCDu), Solar collector shadowing (SCS), and (Solar collector tilt angle (SCT).

The variability of the annual electricity consumption expressed in CV of split and thermosiphon systems were directly correlated with a Coefficient of Determination (R^2) equal to 0.84, which indicates a similar influence of parameters on both system types. Nonetheless, split systems were more sensitive to oscillations on the parameters with the largest impact on both systems. For example, the respective coefficients of variation of thermosiphon and split systems related to the annual electricity consumption were 170% and 202% for solar collector dust accumulation, 77% and 167% for tank heat loss, 127% and 158% for electric back-up heating temperature range, 120% and 134% for solar collector tilt angle, 105% and 125% for solar collection direction, and 75% and 114% for solar collector area. On the other hand, thermosiphon systems were more influenced than split systems by parameters with intermediate influence on SWHs, for which the respective CVs of split and thermosiphon systems were 52% and 79% for end-use water demand, 44% and 75% for end-use water temperature, 54% and 69% for solar collector efficiency, 29% and 54% for tank volume, and 35% and 51% for cold water temperature. The remaining parameters had less than 35% variability for both split and thermosiphon systems. The six largest variabilities in the sensitivity analysis of annual electricity consumption were associated with three site-specific parameters and three technical specifications categories. Thus, in order to attain energy efficiency through the use of SWHs, site-specific conditions must be considered along with technical specifications. Moreover, user behaviour also promoted a significant variation in the electricity consumption of SWHs.

The variability of the solar fraction indicator followed the same trend as the annual electricity consumption, with a direct correlation of 84% ($R^2=0.82$). This similarity is related to the inverse correlation between these two indicators. For instance, their correlation was equal to 95% for thermosiphon systems, and 91% for split systems. The comparison of the solar fraction variability between split and thermosiphon systems revealed a larger sensitivity of the latter system type due to changes in the input parameter classes. Not only did split systems have a consistently higher solar fraction than thermosiphon systems (9% higher on average), but also their solar fraction was more resilient to modifications in technical specifications, site-specific conditions and user behaviour patterns. The solar fraction changeability of split systems was only higher than that for thermosiphon systems for the hot water tank heat loss parameter. For this parameter, the solar energy gains of split systems were consistently 10% above thermosiphon systems for the standard, upper-standard and upper-extreme classes; albeit, for the lower-extreme class, this difference was reduced to only 1%, for thermosiphon systems were not as prone as split systems to heat losses due to their lower average hot water temperature within hot water tanks.

The peak-hour electricity consumption measure in absolute terms ($\text{kWh}\cdot\text{year}^{-1}$) was the most variable indicator. This indicator was particularly influenced by changes in the input parameters of split systems, reaching the single highest variability among parameters ($\text{CV}=973\%$) for the electricity back-up heating position parameter. This extremely high oscillation is associated with an increase in auxiliary heating events when the electric heating element is positioned between the lower half and the bottom of hot water tanks; under these conditions, the peak-hour electricity consumption increased from approximately 17 to a maximum of $381 \text{ kWh}\cdot\text{year}^{-1}$. On the contrary, the position of elements had neutral influence on peak-hour electricity consumption of thermosiphon systems (approximately $91 \text{ kWh}\cdot\text{year}^{-1}$ on average) due to the mixing of hot water into horizontal tanks. Among parameters with impact on both system types, the solar collector direction promoted the largest fluctuation of the peak-hour electricity consumption, i.e. $\text{CV}=254\%$ for thermosiphon systems and $\text{CV}=567\%$ for split systems. The solar collector tilt angle also had a considerable effect on the peak-hour electricity of thermosiphon ($\text{CV}=118\%$) and split ($\text{CV}=370\%$) systems. The electric back-up heating range (hot water tank set-point temperature) showed a significant modification of the peak-hour electricity consumption as well, for which the coefficient of variation of thermosiphon and split systems were 142 and 159%, respectively. The

dust accumulation effect on collectors was associated with a significant expansion of peak-hour electricity consumption of split systems (up to 174 kWh·year⁻¹), and hence it had the third largest influence on the variability of split systems (CV=430%) with a considerably lower significance for thermosiphon systems (CV=46%). Electricity tariffs also played a major role in the peak-hour electricity consumption variability of split systems (CV=85%) and thermosiphon systems (CV=89%), as they can provide a full diversion of electricity consumption from peak-hours. Other parameters had an overall lower significance on the peak-hour electricity variability than the aforementioned parameters.

The variability of the compliance level with *Legionella spp.* control temperature showed a significant lower range than the one for annual and peak-hour electricity consumption. Its average was slightly higher for thermosiphon systems (11%) in relation to split systems (14%). The parameters with the largest influence on the compliance levels of both system types were associated with solar collectors. For instance, the site specific conditions related to the dust accumulation and tilt angle of collectors had the largest variabilities among all parameters, with respective coefficients of variation of 57% for thermosiphon and 60% for split systems, and 39% for thermosiphon and 42% for split systems. Moreover, the specification of the area of solar collectors was also linked to a large variability of *Legionella spp.* control temperatures in relation to other parameters, i.e. CV=34% for thermosiphon systems and CV=37% for split systems. The second most important component of the SWHs in terms of *Legionella spp.* control temperature compliance was the hot water tank. Its auxiliary electricity heating element setting-point temperature was the major parameter to promote variability in the control temperature (CV=34% for thermosiphon systems and CV=25% for split systems) followed by the insulation specification (CV=14% for thermosiphon systems and CV=27% for split systems) and the tank volume (CV=8% for thermosiphon systems and 11% for split systems). The user behaviour also had a significant impact on the control temperature in particular for thermosiphon systems. For instance, the coefficient of variation of the end-use point temperature, time-of-use and demand for thermosiphon systems was 12, 13 and 14%, respectively; while, for split systems, respective results for the same parameters were equal to 5, 8 and 7%. The influence of other parameters on this indicator was not as pronounced as the one of the aforementioned parameters.

The multi-parametric sensitivity analysis indicates a predominant influence of parameters related to solar collectors due to their importance for the adequate performance of SWHs. Among these parameters, direction, dust accumulation levels and area of solar collectors were the most influential parameters related to the total energy consumption variability. The reduced influence of user behaviour parameters on the total energy consumption and *Legionella spp.* control temperature is mainly associated with the adequate design of the standard system, in which the hot water supply is suitable for a range of demand scenarios. Conversely, the impact of user behaviour on peak-hours electricity consumption was significant, revealing the importance of a proactive attitude of households towards daily consumption pattern adjustments to reduce peak consumption. Alternatively, peak-hours electricity consumption can be also eliminated without significant impacts to other performance indicators by adopting off-peak electricity tariffs. Thus, the optimisation of SWHs under a multi-parametric framework encompasses multiple influential parameters, which have to be refined on a case-by-case basis.

4. Key findings

The study showed a significant influence of different technical specifications and site-specific conditions on the performance of SWHs considering both energy and service level indicators. A summary of key findings is presented in the following sub-sections.

4.1. Supply reliability

SWHs can achieve full compliance with comfort requirements (i.e. continuous hot water supply at end-use points at 40 °C) under variable conditions, albeit there may be some time periods where the temperature of systems may not be adequate for *Legionella* spp. growth control (i.e. continuous hot water storage measured at the outlet of the storage tank at 60 °C or more) in particular during cold months.

Care should be practiced in the interpretation of results related to *Legionella* spp. control temperature. As described by Kruse et al. [28], the susceptibility of residential hot water system to *Legionella* spp. proliferation cannot be easily linked to clinical cases of legionellosis. Nonetheless, Mercante and Winchel [27] indicate that the number of legionellosis are likely underestimated due to limitations in diagnostic and detection methods, and that this disease may pose mortality risk among at-risk populations (e.g. immunosuppressed and elderly populations).

4.2. Split versus thermosiphon systems

Split systems have an overall better performance than thermosiphon systems under standard specification and operation conditions. The total annual electricity consumption of split systems was 7% lower than the one for thermosiphon systems, with a reduction in peak-hour consumption of 20% and a 6% higher compliance level with *Legionella* spp. control temperatures. Nonetheless, thermosiphon systems were more energy efficient during summer, when they reached almost 100% solar fraction.

Thermosiphon systems had a better performance under low water demand and temperature patterns, while split systems performed better under high water demand and temperature patterns. For instance, by comparison with the adopted standard user behaviour (155 litres·household⁻¹·day⁻¹ at 40 °C), the upper-extreme classes for temperature (155 litres·household⁻¹·day⁻¹ at 50 °C) and water demand (233 litres·household⁻¹·day⁻¹ at 40°C) promoted an increase in the electricity consumption of 123% in thermosiphon systems; in split systems, the same parameter classes were associated with an expansion in the electricity consumption of 68% and 80%, respectively. On the other hand, the lower-extreme classes for temperature (155 litres·household⁻¹·day⁻¹ at 33°C) and water demand (77 litres·household⁻¹·day⁻¹ at 40°C) were associated with respective electricity saving potentials of 39% and 52% in split systems, and 65% and 76% in thermosiphon systems.

The hot water tank volume had a higher impact on the total annual electricity consumption of thermosiphon systems (CV=54%) than split systems (CV=29%). Conversely, the peak-hour electricity consumption was more influenced by the tank volume in split systems (CV=51%) than thermosiphon systems (CV=21%). For a standard pipe length from the hot water tank to the supply point of 9 meters and standard to upper-extreme levels of pipe insulation (0.75–3.08 W·K⁻¹), electricity saving potentials varied between 14% and 45% for split systems and between 35% and 50% for thermosiphon systems. Split systems are more sensitive to solar collector area variations than thermosiphon systems. Hence, in comparison with thermosiphon systems, the electricity consumption of split systems was 18% higher and 25% lower considering the use of lower-extreme (1.8 m²) and upper-extreme (10.4 m²) solar collector areas.

4.3. Solar collectors

Despite the widespread use of SWHs with lower-standard efficiency solar collectors, there is a significant potential for electricity savings by using more efficient collectors. For instance, the use of more efficient solar collectors showed electricity saving potentials from 65 to 71% for split systems and from 83% to 91% for thermosiphon systems.

The performance of SWHs can decline considerably for solar collector orientations other than north facing, e.g. east and west orientation of collectors may cause a reduction in the electricity saving potential of 80–83% and a decline in

Legionella spp. control temperature to compliance levels of 49–53%. Collectors facing south cardinal and inter-cardinal directions not only lead to a significant decline in the energy performance of SWHs, but also to critical levels of compliance with *Legionella spp.* control temperature (28–36%). The performance of SWHs was also highly influenced by the inclination (tilt angle) of solar collectors. For instance, in relation to the latitude angle, the vertical installation of collectors on the façade of buildings may decrease the solar fraction and the *Legionella spp.* control temperature of SWHs by 56–63%.

In relation to clean solar collectors, the standard level of dust accumulation with a 5% transmittance reduction on the glass of solar collectors promoted an increase in the electricity consumption of SWHs equal to 20–24%. For extreme levels of dust accumulation (i.e. 64% transmittance reduction), the annual electricity consumption of SWHs increased by 5 to 6-fold. North shadowing has the potential to reduce *Legionella spp.* control temperatures and energy saving performance of SWHs by 11–23% and 72–75%, respectively.

4.4. Interconnected systems

The electricity connection influenced considerably the performance of SWHs. Peak-hour electricity consumption can be diverted to shoulder and off-peak-hours by using controlled tariffs without any impact to the *Legionella spp.* control temperature. Moreover, night off-peak tariffs can be used to achieve full diversion of peak-hour and shoulder hour electricity consumption, yet with a decline in the compliance level with *Legionella spp.* control temperatures of 6–9%.

The cold water connection temperature has a direct influence on the performance SWHs. For instance, the electricity savings potential can be improved by 38% to 56% or deteriorated by 52% to 74% with a respective increase or decrease of 6 °C on the average cold water supply temperature.

5. Market applications

Taking into account the conditions assessed in the present study, the energy efficiency and the level of service provided by SWHs could be enhanced through the adoption of the following practices into the SWHs market:

- Split systems is the preferred option for SWHs with medium to large solar collector areas ($>5.5 \text{ m}^2$) in households, while thermosiphon systems have a better performance if solar collectors are undersized.
- The energy performance of split SWHs can be further improved by adopting photovoltaic powered pumps to circulate the heating fluid (water) in collectors. This initiative has the potential to promote electricity saving of 15% on average, and can eliminate any disadvantage of split system in comparison with thermosiphon systems under low water demand and temperature patterns or for undersized solar collectors.
- Thermosiphon systems have a lesser potential to reduce electricity consumption during peak-hours than split systems, and hence they should be a secondary system type adopted into policies aimed at a reduction of peak-hour electricity consumption.
- The service performance of SWHs has to be analysed based not only on the comfort level, but also on the capacity to maintain high hot water storage temperatures to prevent *Legionella spp.* growth. This information has to be shared among all stakeholder groups, including but not limited to users who may deem the performance of systems being satisfactory taking into account the comfort level only. As a result, practices such as the manual activation and inactivation of electric heating elements on power switches by users based on their comfort level should be eliminated to prevent public health risks.
- The set-point temperature of storage tanks can be increased during cold months in order to maintain adequate levels of protection against *Legionella spp.* proliferation. Alternatively, other systems can be used for

disinfection, e.g. ultraviolet disinfection systems coupled to the solar collector and/or water supply circulation loops.

- The adoption of SWHs with efficient solar collectors (standard, upper-standard or upper-extreme classes) will usually be required should higher levels of *Legionella spp.* control and solar fraction be required.
- The installation of solar collectors toward orientations other than north cardinal and inter-cardinal directions must be performed taking into account measures to improve the compliance with *Legionella spp.* control temperatures, including but not limited to: adoption of efficient collectors, increase in the hot water tank set-point temperature, alternative disinfection systems, etc.
- The installation of SWHs with solar collectors oriented to east and west directions must be undertaken under a thorough system performance assessment framework considering site-specific conditions prior to commissioning in order to prevent poor energy efficiency and service levels.
- Considering the significant influence of the cold water temperature on the performance of SWHs, heat recovery from drain water can be implemented to improve the energy efficiency of SWHs by increasing the cold water temperature. An example of such systems is described by Tanha et al. [17].
- The operational performance of SWHs must be assessed periodically or continuously, as variable site-specific conditions (e.g. dust accumulation, trees shadowing, etc.) may have a significant impact on *Legionella spp.* control temperatures and energy performance levels of systems, while maintaining adequate levels of hot water supply at the end-use points with the use of auxiliary heating systems (electric resistance elements). Hence, the “install-and-forget” approach is not suitable for SWHs. This limitation can be overcome with the adoption of automated metering technologies for energy consumption and temperature compliance levels of SWHs with remote data transmission to relevant stakeholders (e.g. households, building administrators, energy retailers, water utilities, health departments and/or energy departments). Depending on the automated metering technology used, a two-way communication with SWHs can be deployed, enabling the remote adjustment of operational parameters (e.g. auxiliary heating temperature set-point, time-of-use of electricity at premises with a single electricity meter and no power interruption during peak-hours, etc.). The economic feasibility of such technologies is increasing with an expansion of microcontrollers and sensors availability, as well as cloud-based big data analytics platforms and the Internet of Things (IoT).
- If a decline in the performance of SWHs is identified or higher levels of performance are required, a mitigation/remediation process can be implemented, which may vary from simple measures (e.g. cleaning up solar collectors) to more complex ones (e.g. installing new components such as new insulation of pipes, frames to position collectors to north orientations at latitude tilt angles, etc.); however, complex initiatives may require government subsidies. A change in the user behaviour may also have a significant impact on the performance of SWHs. For instance, e.g. shifting from an early morning to a late morning water consumption peak may give rise to electricity savings of 14% in thermosiphon and 29% in split systems.
- If night off-peak tariffs are used to increase the solar fraction of SWHs and prevent electricity consumption during peak and shoulder hours, *Legionella spp.* control temperature compliance levels must be assessed and accompanied by additional control measures should it be required.

461

462 **6. Conclusions**

463 The current study examined the influence of different technical specifications and site-specific conditions on the
464 performance of SWHs in residential buildings in Brisbane, Australia. The study was undertaken by employing
465 sensitivity analysis using computational models calibrated with experimental measurements.

466 Results indicate that the annual total and peak-hour electricity consumption and the *Legionella spp.* control temperature
467 of SWHs varied significantly ($CV > 10\%$) with the adoption of different confidence intervals for technical specification
468 parameters, site-specific conditions and user behaviour. Dust accumulation level on collectors is a key site-specific
469 parameter for the energy performance and level of service of SWHs, outplaying several technical specification
470 parameters (e.g. solar collector area and efficiency). Therefore, the development of energy efficiency policies on
471 thermal solar energy use must contemplate directions and best practices on the operation of systems considering
472 site-specific conditions, e.g. frequency of solar collector dust removal events in order to maintain the intended levels of
473 energy efficiency and service as per commissioning process.

474 In this context, performance analysis frameworks for SWHs have to be based not only on technical specification
475 parameters and energy efficiency indicators, but also they must take into account site-specific and user behaviour
476 parameters and level of service indicators.

477

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- Performance frameworks must consider site and user behaviour parameters.
- Policies on SWHs need to provide directions on best practices for operation.
- Dust accumulation on collectors impacts significantly SWHs performance.
- Split SWHs generally outperform thermosiphon SWHs.
- Efficient solar collectors improve the protection against *Legionella* spp.