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Article

Dissemination of Solar Water Heaters in Taiwan: The Case of Remote Islands

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Abstract: Solar water heaters represent the success story in the development of renewable energy in Taiwan. With increasing public awareness, there are over 0.3 million residential systems in operation. To disseminate solar water heaters in remote islands, economic feasibility and water quality are taken into account in this study. The payback period in Kinmen and Penghu Counties are evaluated, according to effective annual solar energy gain, hot water consumption pattern and cost. Assessment of the scaling and corrosion tendencies for solar water heaters using tap and underground water are also presented. For flat-plate solar collectors with metal components, favorable corrosion resistance and protective anti-corrosion coatings are required.

Keywords: solar water heater; remote island; subsidy; payback period; water quality

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1. Introduction

Taiwan is densely populated (23,315,822 persons and 644.21 persons/km^2 in 2012) and has limited natural resources. The ratio of indigenous energy to total primary energy supply is approximately 2.18% in 2012 [1]. Therefore, significant efforts have been devoted during the past three decades toward the development and dissemination of biomass energy, geothermal energy, ocean energy, photovoltaic energy, solar thermal energy and wind power generation [2], despite the intermittent nature of those renewable energy resources. For solar thermal energy, it is known to be the most widely used in many countries [3–7]. In Taiwan, the climatic conditions are predominantly very sunny, with daily average solar radiation of 3.25 kWh/m^2 in the north and 4.64 kWh/m^2 in the south. For promotion of solar water heaters (SWHs), the Bureau of Energy, Ministry of Economic Affairs (BEMOEA, 1986–1991 and 2000–present) and some regional governments have established subsidy programs [8]. The accumulated area of solar collectors installed at the end of 2012 reached 2.25 million square meters (275 m^2 per thousand inhabitants). Chang *et al.* [9] further demonstrated that the market-driven mechanism for SWHs in Taiwan is a multi-parametric phenomenon. In addition to the capital cost of SWHs and energy price index, the potential market is associated with the population structure, urbanization, type of housing and status of new construction.

In Taiwan, gas water heaters dominate the market and there are approximately 0.3 million residential SWHs in operation. It is considered that economic feasibility is one of the dominant factors influencing dissemination of SWHs. According to effective solar radiation, a study by Pan *et al.* [10] indicated that the payback period of SWHs in Taiwan varies from 6 to 15 years in different regions and type of heaters being replaced. In addition, the area of solar collector installed (A_{sc}) of a system and hot water use pattern are among the dominant factors influencing the payback period of SWHs. It is also noted that there has been a drastic increase in the price of natural gas and liquefied petroleum gas during the past few years. However, the state-owned Taiwan Power Company has limited variation of electricity rates due to government intervention for controlling inflation. Therefore, electric water heaters are preferred in remote islands. Further, it is known that over-pumping of underground water causes land subsidence and gradual salinization by seawater in remote islands. Since flat-plate solar collectors comprise metal components (stainless steel, copper, or aluminum), leakage of absorbers, gate valves and deterioration of sealing have been reported from time to time. Therefore, water quality (including scaling and corrosion) on the service life of SWHs should be taken into account.

The remainder of this paper is organized as follows: Section 2 gives a brief introduction of the two major remote islands of Taiwan, Kinmen and Penghu Counties. To evaluate the effective solar energy gain, the climatic conditions (global solar radiation and ambient temperature), collector efficiency and hot water consumption pattern are employed. The Langelier saturation index (LSI), Ryznar stability index (RSI), Puckorius scaling index (PSI), and Larson-Skold corrosive index (LSCI) are adopted as indicators for assessing scaling and corrosion in SWHs. The payback period and water quality are presented in Section 4 and conclusions are drawn in Section 5.

2. Background: Kinmen and Penghu Counties

Kinmen County (118°24' E, 24°27' N) is made up of 12 jurisdictional islands, with a total land area of 151.66 km^2, and lies in the subtropical oceanic climate zone. The annual average temperature is 20.9 °C. The highest and lowest monthly average temperatures are 28.2 °C in August and 12.8 °C in January, respectively. According to the official household registration statistics [11], Kinmen County had 35,374 households and 3.20 persons/household. Penghu County (119°19' to 119°43' E, 23°12' to 23°47' N) is located on the Taiwan Strait between China and Taiwan and lies approximately on the Tropical of Cancer. The total land area is 127.96 km^2. There are six townships and a city in the county with 31,468 households and 2.96 persons/household. Its average temperature of the year is 23 °C; the lowest is 16.2 °C in February and the highest is 28.3 °C in July.

Figure 1 shows the monthly solar radiation per square meter in Kinmen and Penghu Counties [12], with peak values observed in July. The hot water made available by SWHs might exceed the corresponding demand of end users, say from May to October. It is also noted that the monthly solar radiation per square meter in Penghu County is considerably lower than that in Kinmen County in winter (higher demand in hot water supply). Moreover, architectural type of buildings is one of the major concerns for available installation location of SWHs. The results of household questionnaire survey indicated that three- and four-story houses accounted for 36.4% and 38.4% of SWHs installed in Taiwan, respectively [5]. In Kinmen and Penghu Counties, as shown in Figure 2, two- and three-story houses are the major types of housing, say 76.8% and 62.8%, respectively. Therefore, it is considered that the housing status is not the major concern for disseminating SWHs in both counties. Further, it is noted that the units of SWHs installed from 2000 to 2012 were 3336 and 413 in Kinmen County and Penghu County, respectively. Chang *et al.* [8] indicated that the regional subsidy program introduced by the government of Kinmen County was the main force influencing the growth in sales.

Figure 1. Monthly solar radiation per A_{sc} (2005–2011).

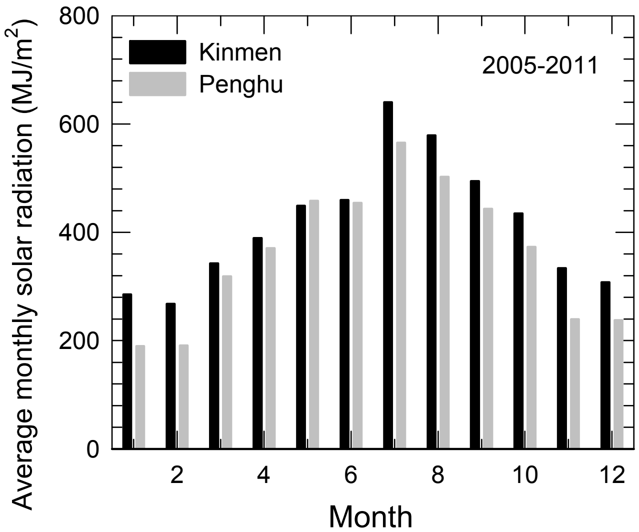
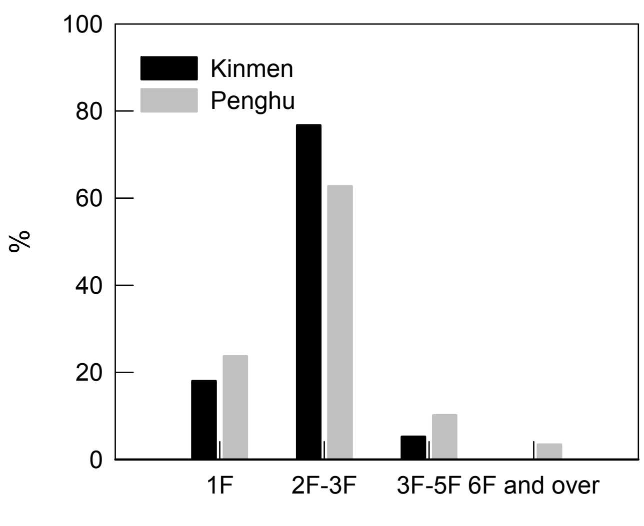


Figure 2. Housing types.



3. Methodology

3.1. Payback Period

The glazed flat-plate type solar collectors with metal absorbers and glass cover are widely used in Taiwan (90% in terms of A_{sc}) [13]. The average unit price (initial cost of a SWH/area of solar collector installed) ranged from 9,100 to 16,250 NTD/m^2 (NTD: New Taiwan Dollar, 1 \$ ≈ 30 NTD). To disseminate SWHs, the subsidy programs have been promoted by the governments, as shown in Table 1. By filling an application form, end users will be granted subsidies according to the area and type of solar collectors installed (2,250 NTD/m^2 for glazed flat-plate and evacuated-tube solar collectors, and 1500 NTD/m^2 for unglazed flat-plate solar collectors). Note that the amount of subsidy was doubled by the BEMOEA on remote islands (such as Kinmen and Penghu Counties). Further, the payback calculation model developed by Kaldellis *et al.* [14] is adopted to estimate the operation cost (C_n), including initial cost of a SWH (IC_o), annual maintenance cost and subsidy. The inflation rate is also taken into account. Total savings (R_n) due to the thermal energy offered by a SWH after n years of operation is evaluated by the net heat output [15] and effective cost of the substituted conventional energy [11]. C_n is examined as a function of service period of the installation. Then the data are employed to compare R_n of a SWH and to determine the payback period.

Table 1. Subsidy programs in Taiwan.

Funding agency	Period	Collector-area-based subsidies
BEMOEA	January 2009–present	Direct subsidy, 2,250 NTD/m^2 for glazed flat-plate SC and evacuated-tube SC; 1,500 NTD/m^2 for unglazed flat-plate SC
Government of Kinmen County	March 2008–present	Direct subsidy, the same amount as BEMOEA; Subsidizing up to A_{sc} = 6 m^2 after 1 April 2010
Government of Penghu County	January 2012–present	Direct subsidy, 3,000 NTD/m^2; Subsidizing up to A_{sc} = 6 m^2

3.2. Water Quality

This study adopted LSI, RSI, PSI, and LSCI as indicators for assessing scaling and corrosion in SWHs. LSI, RSI, and PSI are primarily employed to assess how ions scale in water; this measure is adopted to determine whether metal corrosion is likely to occur [16–22]. LSCI is utilized to calculate a ratio for the combined concentration levels of chlorine and sulfate ions in water to the corresponding alkalinity; this measure serves to estimate the corrosion of low-carbon steel, carbon steel, and aluminum in water at room temperature [20,23,24]. Although no evidence has shown that LSCI can be employed to estimate the corrosion of stainless steel and copper alloys in water, various studies have indicated that stainless steel, copper, and aluminum can demonstrate pitting corrosion in environments that contain chlorine ions [25–28]; and the higher the level of chlorine ion concentration is, the more apparent the pitting corrosion becomes.

Scale formation and corrosion are positively correlated with temperature; as the temperature of a system increases, scale formation and corrosion become more significant [21]. During the summer period in Taiwan, the water temperature inside a SWH can reach 70 °C to 80 °C. A hypothetical temperature of 80 °C was employed to estimate the indicators for assessing scaling and corrosion. In addition, according to the aforementioned research, the corrosion of the metal components in a SWH becomes increasingly evident when the LSI value is less than 0, the RSI value is greater than 7.5, the PSI value is greater than 6.0, and the LSCI value is greater than 0.8. This study assessed corrosion in SWHs at two remote islands of Taiwan: Kinmen County and Penghu County. The data included:

a. Annual average tap-water quality for 2010 and 2011 according to the water purification plants in Kinmen County [29] and Penghu County [30,31];
b. Water sampling from households that used tap water in SWHs [13];
c. Water sampling from households that used groundwater in SWHs [13].

4. Results and Discussion

4.1. Payback Period of SWHs

4.1.1. Energy Savings

The operation cost of a SWH includes the initial and maintenance costs of a system. In the domestic sector, the mean annual rate of consumer price index (=1.38% from 2004 to 2011) and the average one-year interest rate of saving account (=0.949% from 2009 to 2011) are deemed suitable for representing the inflation rate and local annual capital cost, respectively [11]. Then the operation cost can be examined as a function of service period of the installation. For the benefit analysis, the present study focuses mainly on the reduction in consumption of electricity. Chang *et al.* [32] pointed out that the variation in price of domestic electricity was rather limited due to government intervention for controlling inflation, in which the mean annual price change is approximately 0.08 NTD/kWh.

To estimate the annual heat gain of a SWH, daily solar radiation and hot water consumption pattern per person should be taken into consideration. For daily load volumes (L) of 40–120 L, the annual solar energy gain per A_{sc} (L/A_{sc}) in Kinmen County (2005–2011) ranges from 947% ± 4% (40 L/day) to 1670% ± 9% (120 L/day) MJ/m^2, as shown in Figure 3. The lowest performance is associated with the smallest daily load volume, which is consistent with the results obtained by Haralambopoulos *et al.* [33]. In Penghu County, the annual solar energy gain is lower than that in Kinmen County. There is also a large variation in the annual solar energy gain, particularly at higher L/A_{sc}. This demonstrates the system economics in Kinmen County. Further, the conversion factor and the heating efficiency for electricity are 3.60 MJ/kWh and 90%, respectively. Figure 4 shows the L/A_{sc} on electricity being substituted by solar energy during 2005–2011 in Kinmen and Penghu Counties. It is obvious that there is a reduction in consumption of electricity with increasing L. For example, reduction of electricity by a SWH ranges from 292% ± 4% to 512% ± 9% kWh/A_{sc} in Kinmen County.

Figure 3. Effective annual solar energy gain.

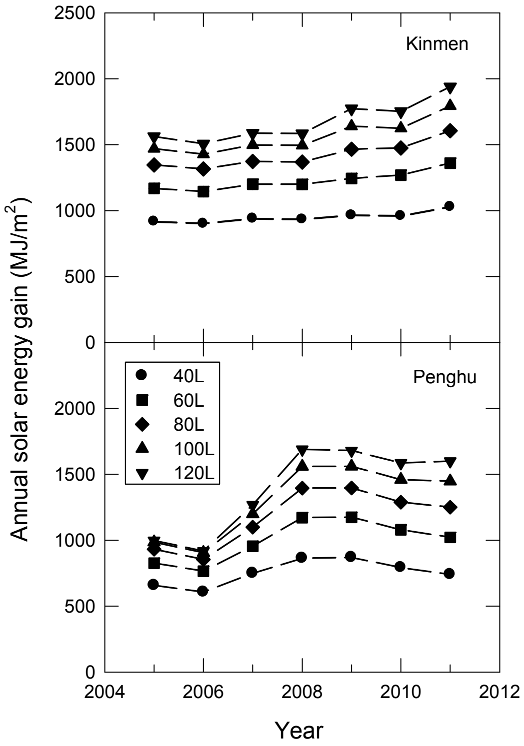
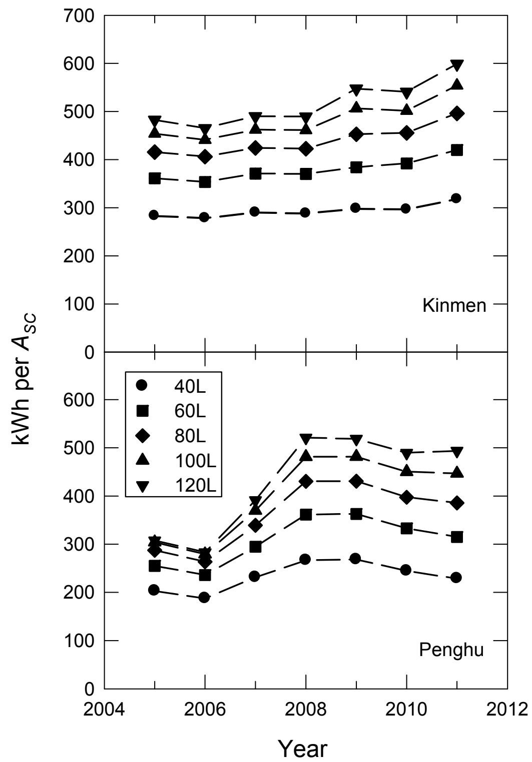


Figure 4. L/A_{sc} on electricity being substituted by solar energy.



4.1.2. Benefit Analysis

R_n can be examined as a function of service period of the installation. The benefit with electricity being substituted under different L/A_{sc} is calculated, as shown in Figure 5. With a 20-year service period, the monetary benefit is 18,000–31,600 NTD/m^2 with L/A_{sc} = 947–1670 MJ/m^2 in Kinmen County, while it is 15,250–27,200 NTD/m^2 with L/A_{sc} = 748–1334 MJ/m^2 in Penghu County. Further, the dominant factors on the payback period of SWHs are operation cost, subsidization and L/A_{sc}. For a given L/A_{sc}, the payback period as a function of unit price of a SWH can be deduced from Figures 3 and 4. As shown in Figure 6, the payback period increases linearly with the unit price of a SWH. In Figure 7, the effect of L/A_{sc} (IC_o = 12,250 NTD/m^2) on the payback period is presented. For L/A_{sc} less than 947 MJ/m^2, a SWH is least utilized. The corresponding payback period exceeds 10 years in both counties. With increasing L/A_{sc}, there is a downward trend, in which the payback period is 5.56 years with L/A_{sc} = 1670 MJ/m^2 in Kinmen County. Therefore, there is a beneficial effect with increasing L/A_{sc}. An end user should determine the economically optimal A_{sc} according to the hot water consumption pattern of each household.

Figure 5. Benefits in terms of reduction in electricity consumption.

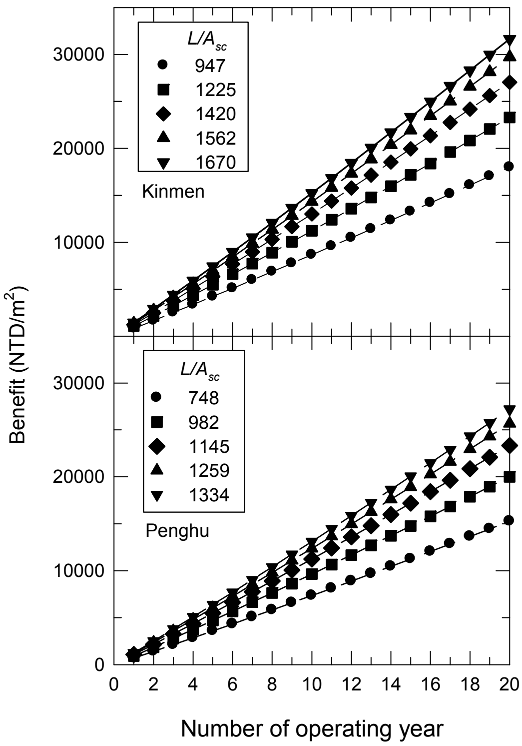


Figure 6. Payback period as a function of unit price of SWHs.

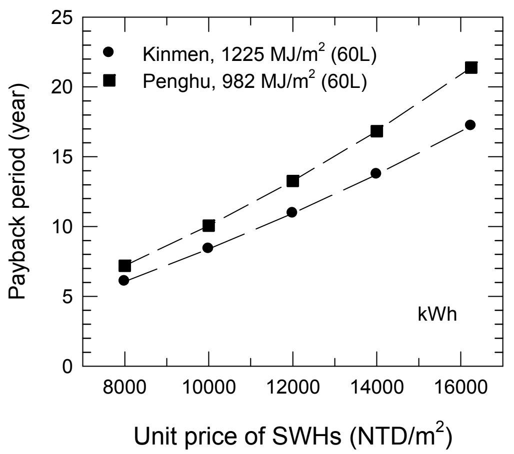
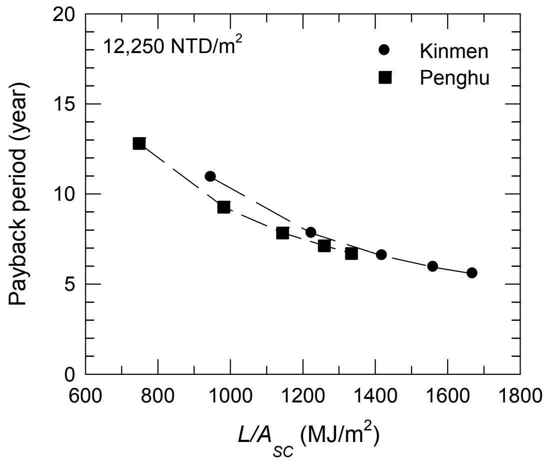


Figure 7. Payback period as a function of L/A_{sc}, IC_o = 12,250 NTD/m^2.



4.2. Water Quality on SWHs

4.2.1. Water Quality in Penghu County

The corrosion data in Penghu County are listed in Table 2. In 2010, at the Cheng-Kung Water Purification Plant (WPP), all LSI, RSI, and PSI values accorded with the LSCI value. In contrast that from Cheng-Kung WPP, the tap water from other WPPs demonstrated a higher level of corrosion. Both LSI and RSI values also suggested that the tap-water quality tended to scale while the PSI value suggested that the tap-water demonstrated a slight tendency to corrode. However, most of the LSCI values surpassed 0.8, indicating a serious corrosion problem in the tap water. The contradictory results in Table 2 may attributed to the fact that LSI, RSI, and PSI estimations involved using calcium carbonate saturation to assess the likelihood of scale formation in solution and scale demonstrated a certain ability to prevent corrosion. In addition to calcium carbonate saturation, the pH buffer capacity of a solution was also included in the estimation of PSI values. A pH value for PSI calculated was calculated according to the balanced hydrogen-ion activity in a solution, rather than measuring the PH with the relevant apparatus. Therefore, the resulting PSI value is more accurate in reality compared with both LSI and RSI values. The LSCI value was estimated using the ratio of the combined concentration levels of chloride salt and sulfates to the alkalinity. The LSCI takes into account chloride and sulfate corrosion on the materials. The alkalinity of water can be employed to measure acid buffer capacity, and low-alkalinity water solution can easily form acidic or corrosive environments.

Table 3 shows the analysis results of water samples from households that use SWHs in each town [13]. However, the analyses from 2010 to 2012 lacked sulfate analyses. Therefore, the LSCI estimation did not include sulfate concentration levels, resulting in underestimated LSCI values. Thus, the LSCI results should be increased for future applications. As seen in Table 3, both LSI and RSI values suggested a tendency to cause scaling, while the PSI values indicated a slight trend to cause corrosion. All LSCI values for Baisha Township, Husi Township, Shiyeu Township, and Magong City were close to or greater than 1.2, implying a serious corrosion problem. These results are similar to those shown in Table 2. In addition, it is also shown that the chloride salt concentration levels were typically higher than 130 mg/L. Thus, for Penghu County, it can be inferred that using tap water to supply SWHs caused a high risk of corrosion.

Table 2. Assessment of scaling and corrosion tendency in Penghu County [30,31].

WPP	Cheng-Kung		Wang-An		Cimei		Siyu	
Year	2010	2011	2010	2011	2010	2011	2010	2011
Cl^-, mg/L	131 ± 27	124 ± 23	165 ± 27	194 ± 36	257 ± 125	155 ± 27	198 ± 34	217 ± 39
LSI	−0.76 ± 0.46	−0.03 ± 0.58	0.26 ± 0.28	0.97 ± 0.34	0.99 ± 0.74	0.85 ± 0.36	0.13 ± 0.43	0.35 ± 0.15
RSI	8.05 ± 0.74	7.53 ± 1.00	6.73 ± 0.33	6.04 ± 0.56	5.62 ± 1.14	5.88 ± 0.62	7.25 ± 0.66	6.92 ± 0.23
PSI	7.70 ± 0.92	8.08 ± 1.61	6.72 ± 0.39	6.91 ± 0.76	5.67 ± 1.12	6.02 ± 0.85	7.19 ± 0.52	6.93 ± 0.25
LSCI	5.60 ± 2.04	4.91 ± 3.26	3.99 ± 0.47	5.30 ± 2.69	2.55 ± 0.54	2.12 ± 0.99	1.83 ± 0.16	1.84 ± 0.16
WPP	**Jibei**		**Baisha**		**Lintou**		**Magong**	
Year	2010	2011	2010	2011	2010	2011	2010	2011
Cl^-, mg/L	297 ± 47	330 ± 108	163 ± 34	225 ± 116	133 ± 41	109 ± 26	128 ± 43	106 ± 28
LSI	1.40 ± 0.23	1.58 ± 0.13	0.01 ± 0.73	1.24 ± 0.62	0.56 ± 0.22	0.74 ± 0.26	0.30 ± 0.23	0.54 ± 0.51
RSI	5.52 ± 0.48	5.27 ± 0.26	6.89 ± 1.03	5.25 ± 0.88	7.01 ± 0.20	6.74 ± 0.47	7.47 ± 0.42	7.04 ± 0.87
PSI	6.23 ± 0.54	6.15 ± 0.41	6.20 ± 0.87	4.92 ± 0.78	8.24 ± 0.14	7.93 ± 0.68	8.87 ± 1.04	8.28 ± 1.37
LSCI	2.57 ± 0.50	3.35 ± 1.34	1.74 ± 0.70	0.95 ± 0.29	3.69 ± 1.21	2.75 ± 1.26	6.79 ± 6.66	4.08 ± 2.50

Table 3. Assessment of scaling and corrosion tendency-tap-water quality in Penghu County [13].

Township	Baisha	Husi	Siyu	Magong
Cl^-, mg/L	350 ± 30	188 ± 83	208 ± 43	140 ± 9
LSI	1.38 ± 0.67	0.74 ± 0.11	0.26 ± 0.33	0.07 ± 1.21
RSI	5.01 ± 0.62	6.47 ± 0.68	7.05 ± 0.28	7.58 ± 1.99
PSI	4.76 ± 0.02	7.07 ± 1.50	7.04 ± 1.11	8.55 ± 1.99
LSCI	1.47 ± 0.43	2.22 ± 0.23	1.72 ± 0.08	4.97 ± 3.38

For SWHs using underground water, the water sample analyses for households in Baisha and Husi Townships are shown in Table 4. All LSI, RSI, and PSI results suggested that the underground water in both Baisha and Husi Townships caused scaling. The LSCI estimation did not include sulfate concentration levels, resulting in underestimated LSCI values; however, the LSCI estimates did suggest that the underground water caused slightly elevated levels of corrosion. The concentration of chloride salt in the underground water of Baisha and Husi Townships were higher than 130 mg/L. Thus, for Penghu County, it can be inferred that using underground water to supply SWHs posed a high risk of corrosion.

Table 4. Assessment of scaling and corrosion tendency-underground-water quality in Penghu County [13].

Township	Baisha	Husi
Cl^-, mg/L	320 ± 71	209 ± 54
LSI	1.07 ± 0.02	1.42 ± 0.64
RSI	5.70 ± 0.83	5.16 ± 0.71
PSI	5.76 ± 1.87	5.42 ± 0.38
LSCI	1.96 ± 0.26	1.46 ± 0.86

4.2.2. Water Quality in Kinmen County

In Kinmen County, the water-quality analyses conducted by the Kinmen County Waterworks [29] lacked alkalinity and sulfate analyses. However, alkalinity is a crucial parameter for assessing scale and corrosion tendencies. Therefore, the analyses of the Kinmen County Waterworks were not employed in this study. Table 5 shows the analysis results of water sample from households in Kinmen County that used tap water to supply SWHs [13]. All LSI, RSI, and PSI estimates for Jinsha Township, Jincheng Township, Jinning Township, and Lieyu Township suggested that the tap water caused slightly elevated levels of corrosion. These results were similar to those of the LSCI estimates. Regarding Jinhu Township, all LSI, RSI, and PSI estimates suggested that tap water caused slightly elevated levels of scaling, whereas the LSCI estimate suggested a relatively higher corrosion tendency. All LSI, RSI, and PSI estimates showed a scaling tendency resulted from the high levels of alkalinity and hardness in water of Jinhu Township. In addition, the elevated LSCI estimate that suggested a high corrosion tendency was due to the high concentration of chloride salt in Jinhu Township. Table 6 shows the analysis results of the water sample from households in Kinmen County that used underground water to supply SWHs. As can be seen, the concentration of chloride salt in the underground water of Kinmen County typically ranged from 35 to 130 mg/L. All LSI, RSI, and PSI estimates for the underground water in each township suggested a relatively higher corrosion tendency, which concurred with the LSCI estimate. Thus, for Kinmen County, it can be inferred that using either tap water or underground water to supply SWHs posed an elevated risk of corrosion.

Table 5. Assessment of scaling and corrosion tendency-tap-water quality in Kinmen County [13].

Township	Jingsha	Jincheng	Jinhu	Jinning	Lieyu
Cl^-, mg/L	27 ± 13	96 ± 73	322 ± 168	38 ± 4	31 ± 14
LSI	−0.37 ± 0.00	−1.15 ± 0.72	0.92 ± 0.70	−1.85 ± 0.42	−0.65 ± 1.42
RSI	8.35 ± 0.26	8.93 ± 1.02	6.05 ± 0.66	10.40 ± 0.23	8.01 ± 2.14
PSI	9.24 ± 0.55	8.80 ± 0.82	6.70 ± 0.13	10.96 ± 1.04	7.68 ± 1.90
LSCI	0.87 ± 0.37	2.71 ± 1.41	4.77 ± 2.87	3.75 ± 3.10	0.77 ± 0.75

Table 6. Assessment of scaling and corrosion tendency-underground-water quality in Kinmen County [13].

Township	Jingsha	Jincheng	Jinhu	Jinning	Lieyu
Cl^-, mg/L	42 ± 12	77 ± 49	91 ± 52	30 ± 13	55 ± 24
LSI	−0.89 ± 0.63	−1.01 ± 0.51	−1.14 ± 1.78	−3.68 ± 0.36	−0.25 ± 0.38
RSI	8.78 ± 0.80	8.76 ± 0.73	8.68 ± 1.70	12.17 ± 0.25	7.42 ± 0.93
PSI	9.16 ± 0.43	8.82 ± 0.50	8.40 ± 1.57	11.31 ± 0.44	6.89 ± 1.20
LSCI	1.56 ± 0.23	2.70 ± 1.82	3.34 ± 2.32	4.99 ± 0.51	0.56 ± 0.15

5. Conclusions

Higher cost of SWHs compared with conventional hot water heaters is one of the factors limiting installation of these systems. In the payback period analysis, the daily load volume plays an important role in proper sizing of a SWH. An end user should determine the economically optimal area of solar collector installed according to the hot water consumption pattern of each household. Further, the number of SWHs installed in Penghu County is appreciably lower than that in Kinmen County. This might partially be due to less effective annual solar energy gain in Penghu County. Nevertheless, the regional subsidy programs also affect the local market.

LSI, RSI, PSI, and LSCI estimates were employed to assess scaling and corrosion tendencies. The results show that the corrosion in SWHs in Penghu and Kinmen Counties, which may result in a decrease in service life of SWHs, is associated with relatively high concentrations of chlorine ions in water. To solve corrosion problems in SWHs for the remote islands of Taiwan, it is recommended that manufacturers choose metals with favorable corrosion resistance and employ protective anti-corrosion coatings. Regarding corrosion-resistant metals, it is suggested that 316 stainless steel, alloys that possess high levels of chromium, nickel, or molybdenum content, or titanium alloys be selected to replace the commonly used 304 stainless steel. To employ protective anti-corrosion coatings, appropriate methods must be chosen to avoid hazards to human health. It also noted that a longer payback period is expected considering the impact of corrosion.

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Conflicts of Interest

The authors declare no conflict of interest.

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