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Techno-economic Feasibility of Solar Water Heating System: Overview and Meta-analysis

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Abstract:

Solar water heating system (SWHS) has been increasingly adopted for domestic hot water production (accounts for 20% of global household energy use), spacing heating, and thermal façade. Although several reviews on SWHS technological development are available, a literature review on the techno-economic viability of SWHS is lacking, which is critical for practical application of this technology. This paper aims to provide an overview of the existing the techno-economic analyses of SWHS. The technology level, supplementary energy type, natural conditions and policy support are identified as key factors influencing the payback period of SWHS. Meta-analyses are conducted to analyse the effects of these key factors on the payback period. A regression model is developed, considering several study characteristics such as the methodology, continent and study year. The results show 9 negative effects (evacuated tube collector, number/area of collectors, use diesel as supplementary fuel, radiation, specific region, residential sector, numerical estimation and study conducted in Europe) and 7 positive effects (tank water temperature required, hot water consumption pattern, computer modelling/simulation, experiment, case study, study conducted in Asia and South America) on the payback period of SWHS. This study provides useful information to improve the techno-economic performance of SWHS for wider applications.

Abbreviations:

SWHS, Solar Water Heating System; rTWT, required Tank Water Temperature; FPCs, Flat Plate Collectors; ETCs, Evacuated Tube Collectors; HTF, Heat Transfer Fluid; PCM, Phase Change Material; LPG, Liquefied Petroleum Gas; NPV, Net Present Value; IRR, Internal Rate of Return; PP, Payback Period; BCR, Benefit Cost Ratio; LHTES, Latent Heat Thermal Energy Storage; ICS, Integral Collector Storage; EHS, Electrical Heating System; SHS, Hybrid Solar Heating System; ORC-VAR, Organic Rankine Cycle and Vapour Absorption Refrigeration; ESR, Effective Solar Radiation; CDM, Clean Development Mechanism; LHP-STF, Loop-Heat-Pump Solar Thermal Façade.

Keywords: solar water heating system; techno-economic analysis; review; meta-analysis; payback period.

1. Introduction

Solar energy is one of the most abundant renewable resources which has been extensively used for power and hot water generation over the past decades. Solar water heating system (SWHS) is a dominant form of clean, sustainable and efficient solar energy application, which is able to capture the solar radiation and heat up water for domestic hot water use or space heating. According to International Renewable Energy Agency [1], the installed capacity of SWHS has been continuously increasing in the past ten years and reached 435 GW in 2015, which is much higher than that of both solar photovoltaics (227 GW) and concentrating solar thermal power (4.8 GW).

From the global renewable market prospect, the annual investment in the solar energy market reached 81 billion USD in 2015, and more than 50% investment among all the renewable energy resources went to solar PV technology. Regarding the world energy policies, solar and wind energy-related policies are the most extensively adopted and promoted by policy makers, and they are effectively implemented to support the development of solar and wind energy by means of legislative and regulatory policies, Feed-in-Tariff policies, subsidy policies and tax-reduction policies, etc [2].

While the SWHS technology has demonstrated a great potential for future hot water supply, conventional hot water in many countries is still generated by electrical heating or gas combustion, which emitting greenhouse gas and various pollutant. Official statistics show that hot water supply in homes consumes 14-37% of the average household electricity globally [3]. The extensive adoption of SWHS technology could significantly reduce the fossil fuel consumption and greatly minimize greenhouse gas emissions. With the growing importance of SWHS application, extensive researches were conducted to improve the efficiency of SWHS. The future research directions and applications of SWHS were discussed, such as the use of nanofluid [4] and phase change materials [5] in the thermal system (e.g. Gautam et.al [6], Jaisankar et.al [7], Tian and Zhao [8]).

Although extensive research papers and some excellent review papers are available in the literature, they focus on the technological developments of SWHS. Quite a number of techno-economic analyses have been published on particular types of SWHS for various applications and in different countries/regions, showing different techno-economic performances of SWHSs. The economic viability of SWHS is a critical factor for a wider adoption of SWHS since impressive investment revenue is crucial for policy makers and for investors. For these reason, this paper aims to i) systematically review the existing techno-economic analyses on SWHS in the literature and ii) to conduct a meta-analysis on the techno-economic feasibility of SWHS. Meta-analysis is a technique to elaborate and synthesize separate and scattered results or evidence from different studies into a single analysis, and it is able to convert qualitative information to quantitative statistics [9]. In this study, both fixed-effect model and random-effect model are applied to investigate the statistical significance of the independent variables and moderator variables on the payback period estimations of SWHSs. The independent variables include technology level, natural conditions, substituted fuel types as well as policy supports based on the overview in Section 2. The moderator variables include study methodology, studied continent and the year of publication.

The rest of this paper is organized as follows. Section 2 provides an overview of the previous techno-economic feasibility analyses on SWHSs. Section 3 checks the publication bias. Section 4 introduces the methodology, followed by discussions on the meta-analysis results in Section 5. Section 6 concludes the paper.

2. Overview of the Techno-economic Feasibility Analysis of SWHS

In this section, the previous techno-economic analyses of SWHS are summarized in Table 1. The techno-economic feasibility of SWHS in residential sector is most frequently analysed by researchers since domestic hot water consumption accounts for 20% of household energy use, thus SWHS is widely and mainly employed for domestic hot water generation on the roof-top or terrace. For comparison, only a few studies considered the application of SWHS in industrial and agricultural sectors [10][11][12][13][14][15]. In references [16][17][18][19][20][21][22]

[23][24][25][26][27], a number of methods were proposed to improve the SWHS efficiency, such as replacing Flat Plate Collectors (FPCs) by Evacuated Tube Collectors (ETCs), using anti-freeze HTF, heat pumps, and PCM or insulations for storage tanks. In these studies, the economic feasibility by different appraisal approaches was also evaluated. Besides, [28][29][30][31][32] investigates the techno-economic feasibilities on the application of SWHSs for solar space heating (e.g. various solar technologies such as solar floor/wall/ceiling heating and solar thermal façade).

All the selected researches in Table 1 are conducted by computer modelling/simulation, experiment or case study. Some practical parameters are also summarized since these parameters could affect the system's dynamics and thus affect the thermal performance as well as the economic viability. Therefore, in Table 1, the parameters consist of the proposed SWHS, the backup fuel (i.e. electricity, town gas, LPG), the required tank water temperature (rTWT), the number/area/capacity of the collectors, and the discount rate (r) under the specific region or country. The thermal performance is presented by solar fraction (%), system efficiency (%) and energy saving. The economic viability is presented by net present value (USD), internal rate of return (%), benefit-cost ratio and payback period (year). As some researches examine the subsidy policies on promoting the application of SWHS, the subsidy level is considered as an input parameter.

Country	system	Back up fuel (USD)	rTWT (°C)	No./area/ capacity of collectors	Solar fraction (%)	System efficiency (%)	Annual Energy saving	Discount rate	NPV ($)	IRR (%)	PP (year)	BCR	Subsidy
Techno-economic Feasibility of SWHS in Industrial and Agricultural Sectors													
Australia [10]	LHTES[1] in ICS[2]	Natural gas $/m^3$ (0.25 for low, 0.5 for high, 0.75 for year 2035)	120°C to 150°C		35% to 60%	Up to 100%	113,900 to 177,400 kWh	6%			21 to 25 years for low price, 11 to 13 years for high price, 7 to 8 years for 2035.		50% cost reduction
Mexico [11]	ETC vs PTC	Electricity (0.1 $/kWh) Natural gas (6 $/MMBtu)	107.4°C	ETC: 180m^2 PTC: 220m^2	ETC: 38% PTC: 56%		ETC: 67.3% saving PTC: 80% saving	10%	ETC (with subsidy): -170,626 to 12,460 PTC: -194,570	ETC (with subsidy: -11.2% to 14.6% PTC: -12.48%	ETC (with subsidy: 20 to 5.1 years PTC: 18.79 years		0, 25%, 50%, 75%
South Africa [12]	Large-scale SWHS	Coal: 0.022 $/kWh		120.7m^2	67.8%	40.3%	11,769 L paraffin saving	6%		16.7%	9.3 years		
South Korea [13]	Linear vs spot Fresnel lens solar collector	Electricity (0.055 $/kWh)		9.89 m^2 with storage capacity 50kg to 125kg	LFL: 60% to 77% SFL: 64% to 86%			0.5% to 2%			LFL: 25 to 13 years SFL: 24 to 11 years		

Tunis [14]	EHS[3] vs SHS[4] (with ETC)	Electricity	Minimal 16 °C of soil temperature at night	3 ETC	46%						3 years		
Malaysia [15]	Combined ORC-VAR[5]						1.74 for 3.5kW, 2.30 for 7.0kW		10,894	5.6% for 3.5kW, 8.9% for 7.0kW	12.4 for 3.5kW, 9.7 years for 7.0kW		
Techno-economic Feasibility of SWHS in Residential Sector for Domestic Hot Water Usage													
Spain [16]	Active + ETC	Diesel (0.58 \$/L to 0.70 \$/L)	40°C to 80°C	9-11 of $2m^2$ collectors		66% to 55%		4%	10,482 to 6,722	9.9% to 7.2%	10.7 to 13.7		
Tunisia [17]	FPC vs ETC	Electricity (0.1508 \$/kWh) Town gas (0.2486 \$/kWh)	45°C	$2m^2$	FPC: 68% ECT: 84%		FPC: 1316 kWh electricity per year, 306 m^3 town gas. ETC: 1459 kWh per year, 410 m^3 town gas	3%			FPC: 8years based on electricity, 6 years based on town gas ETC: 10 based on electricity, 7.5 years based on town gas		
Mexico [18]	FPC vs ETC in combisystem		45 °C for hot water, start to work when less than 21 °C for radiant floor	12 PFC, Or 8 ETC	FPC: 92.14% ETC: 92.51%	91%		4%			PFC: 9years ETC: 11years		

Saudi Arabia [19]	Passive, ETC vs FPC	Electricity (0.03 $/kWh)	60°C	ETC: 3 m^2 FPC: 2.2 m^2	One single ETC: 64% One glazed FPC: 47%		One ETC:20 to 37 MWh One FPC: 20 to 35 MWh	2.5%			ETC: 4 to 9 FPC: 3.8 to 12.8	ETC: 1.25 to 3 FPC: 0.9 to 3.15	
Canada [20]	Active, closed loop, anti-freeze fluid	Electricity (0.077 to 0.172 $/kWh) Natural gas (0.203 to 0.479 $/$m^3$)		1.5m^2			Electricity: 9,190 TG Natural gas: 13,530 TG	3%, 6%, 9%			2, 6, 10		
China [21]	Active + insulation	Coal: 0.174 $/kg	50°C		78%	65%	4193 kgce	4.85%			4.4 years		
Oman [22]	SWHS	Electricity 0.062 $/kWh					1859 GWh	7.55%	$536	16.7%	6 years	1.36	
China [23]	SWHS			1.5m^2			i.e. Shanghai: 460.2 kWh per 1.5m^2 per year	4%		i.e. Shanghai: 5.3% to 18.4%	i.e. Shanghai: 6.1 to 11.8		0, 13%, 26%, 39%
Taiwan [24]	SWHS	Electricity LPG LNG	42°C			90% for electricity, 80% for LPG and LNG					L/Asc[6]=1216 MJ/m^2, 5.6 to 21.1 years		16% to 25%, could cover the hot water needs for using SWHS.

											L/Asc=1647 MJ/m2, 5.6 to 7.4 year		
Taiwan [25]	ESR[7] based SWHS	Electricity (0.089 \$/kWh) Diesel (0.912 \$/L) Natural gas (0.481 $\$/m^3$) LPG (0.435 \$/L)				90% for electricity, 80% for others	7112 MJ to 9044 MJ	1.86%			Electricity: 11 to 15 years Diesel: 6 to 8 years Natural gas: 12 to 15 years LPG: 11 to 13 years		Subsidy of 74.625 $\$/m^2$ is analysed
India [26]	SWHS		Residential: 40°C Hospital: 50°C Hotel: 60°C	Residential: $1548m^2$ Hospital: $44m^2$ Hotel: $114m^2$			Residential: 930,000 kWh Hospital: 40,000 kWh Hotel: 130,000 kWh				Residential: 4.88 to 4.98 years Hospital: 2.2 to 3.5 years Hotel: 2.14 to 2.29 years		
India [27]	Active	Electricity (0.06 to 0.09 \$/unit) LPG (0.30 to 0.47 \$/unit)					Electricity: 1167 kWh LPG: 140kg		Electricity: -18 to 249 LPG: -162 to -18		Electricity: 6.5 to 3.7 years LPG:10.9 to 6.5 years Natural gas: 8.0 to 5.5 years	Electricity: 1.0 to 1.6 LPG:0.6 to 1.0 Natural gas:0.8 to 1.1	CDM[8]

		Natural gas (0.34 to 0.47 $/unit)					Natural gas:162m^3		Natural gas: -85 to 44				
Techno-economic Feasibility of SWHS in Residential Sector for Space Heating													
Morocco [28]	SFH	Electricity: 0.1047 $/kWh Butane gas:1.042 $/kg	35°C	4m^2	65.3% to 96.5%		At least 72%				Electricity: 6.1 years Butane gas: 8.5 years		
UK [29]	Solar-wall heating (SWH)	gas	Water temperature 20°C higher than ambient, wall structure temperature set as 18°C	5m^2 for tenement flat 30m^2 for bungalow		75%					16 years		
Hong Kong [30]	Centralized SWHS vertical façade		60°C to 65°C	840m^2 (or 3.75m^2 per apartment)	53.4%	38.4%	1146 GJ				9.2 years		
Europe [31]	LHP-STF[9]	Gas/ electricity			39.5% to 58.0%		32360.8 kWh to 45184.0 kWh	8%	90,791 to 218,125	34% to 66%	3.1 to 4.8 years		Stockholm: 6209 $/yr London: 0.23 c/kWh Madrid: N/A
Germany [32]	Façade-integrated solar thermal systems										Max. 10 years		99.25 $/m^2 for small installations up to 40m^2

Table 1. Summary of previous research on the techno-economic feasibility of SWHS in residential, industrial and agricultural sectors

[1] Latent Heat Thermal Energy Storage: the cylindrical LHTES units rely on a cylindrical shell-and-tubes design to segregate the HTF from the PCM.

[2] Integral Collector Storage

[3] Electrical Heating System

[4] Hybrid Solar Heating System. The EHS allowed an increase in inside air temperature of 4°C while SHS permitted temperature rise of 2 °C.

[5] A combined plant of organic Rankine Cycle and vapour absorption refrigeration (ORC-VAR) cycle is proposed for electrical power and chilled water co-production.

[6] L/Asc is used to represent the daily volume loads per collector area.

[7] A proposed of concept of effective solar radiation (ESR), which is based on potential heat output estimated using tap water temperature and solar radiation in each region in Taiwan.

[8] Clean Development Mechanism, which is a protocol between developing countries and industrialized countries that the latter invests emission reduction projects in the former in order to achieve a specific target

[9] Loop-heat-Pump based solar thermal façade (LHP-STF): this system joined the outdoor and indoor parts via connection of transport lines.

3. Check of Publication Bias

23 research works on the techno-economic analyses of SWHS are summarized in Table 1. For each research, the number of observations, the minimum and maximum payback period estimations, the studied country and publication year are summarized in Table 2. Overall, the 23 researches have made 110 payback period estimations with a mean of 8.58 years, the minimum and maximum 2 years and 29 years, respectively. A better visual grasp of how the 110 payback periods are distributed is illustrated in Fig. 1. The histogram indicates that the estimated payback periods are slightly scattered with more than 29% for 4-6 years and small amount of them for over 20 years.

Study ref.	Mean pp	Min. Pp	Max. Pp	N	Country	Publication year
[10]	7.5	7	8	2	Austrilia	2017
[11]	17.23	4.1	29	4	Mexico	2017
[12]	9.3	/	/	1	South Africa	2016
[13]	16.25	11	24	4	South Korea	2015
[14]	3	/	/	1	Tunisia	2015
[15]	11.05	9.7	12.4	2	Malaysia	2012
[16]	12.24	10.7	13.7	5	Spain	2016
[17]	8.75	7.5	10	2	Tunisia	2013
[18]	11	/	/	1	Mexico	2016
[19]	4.76	3.4	9	10	Saudi Arabia	2016
[20]	6	2	10	3	Canada	2014
[21]	4.4	/	/	1	China	2016
[22]	10	/	/	1	Oman	2012
[23]	7.73	5.3	17.8	27	China	2014
[24]	9.6	5.5	15	5	Taiwan	2015
[25]	11.13	6	15	16	Taiwan	2012
[26]	6.92	4.88	12	5	India	2007
[27]	6.85	3.7	10.9	6	India	2008
[28]	7.3	6.1	8.5	2	Morocco	2017
[29]	16	/	/	1	UK	2012
[30]	9.2	/	/	1	Hong Kong	2006
[31]	3.91	3.1	4.8	9	Europe	2015
[32]	6	/	/	1	Germany	2014
OVERALL	8.58	2	29	110		

Table 2 Payback period estimations

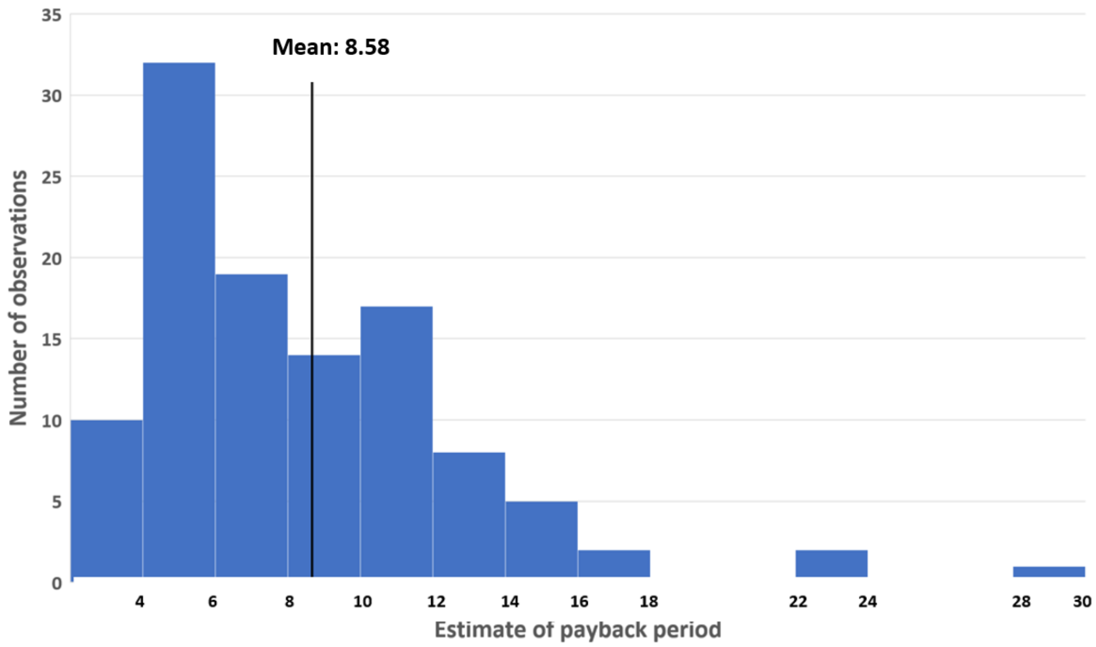

Figure 1. Histogram of payback period estimations distribution

Publication bias is a phenomenon that occurs when the results of a study are crucial to influence the quality of the study, and the results in published studies are systematically different from unpublished studies [33]. Several factors could affect the direction and nature of the results in a study including subjective reasons such as experienced researchers are more conscious of what kind of results could be accepted by journal reviewers [34]; and objective reasons such as [35] indicates that 19.6% of unpublished studies are due to unimportant results. In this paper, the techno-economic analysis of SWHSs and the payback period estimations are all extracted from published studies. Nevertheless, it is reasonable to doubt the presence of publication bias of this study, and thus checking the publication bias of the results are of importance.

To check the publication bias, funnel plot is employed with the x-axis denoting the mean of 110 estimations payback period, and y-axis denoting the standard error of each study. When the results in the study are with larger sample size and smaller standard errors, the point will be clustered towards the top of the funnel, and vice versa. A relatively symmetric funnel plot indicates less possibility of publication bias. Figure 2 shows the funnel plot of 23 selected papers in meta-analysis. It is obvious to read the plots symmetrically distributed within the funnel, representing the absence of publication bias. However, it should be noted that the funnel plot method is an informal and simplified way to check publication bias. Therefore, this paper further employed a more formal and more accurate statistical test to double check the publication bias – the Begg's test [36]. As a result, Begg's test suggests no evidence of publication bias since p-value is 0.43705.

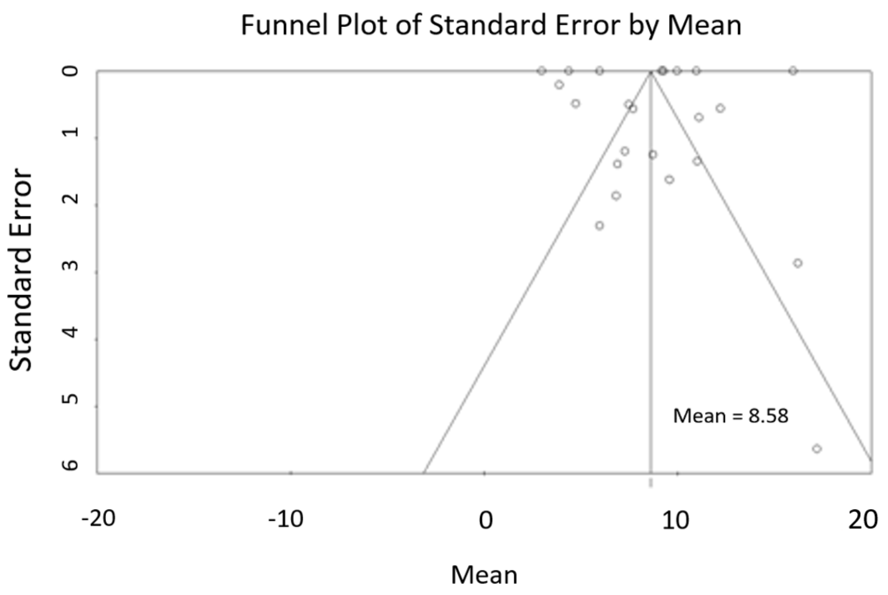

Figure 2. Funnel plot of publication bias

4. Methodology

4.1. Coding of Independent Variables and Moderator Variables

The independent variables and moderator variables used in meta-analysis are summarized in Table 3, and the coding of these variables are elaborated in Table 4. The description column in the table describes the meaning of variables. If the original paper focuses on any of the variables, a dummy "1" is marked as categorical variables for all moderator variables except dummy "6-17" for "year" as continuous variable. For instance, one of the 23 papers focuses on renewing the incentive program of SWHSs in

China with the cost effectiveness estimation methodology in year 2014. Therefore, the code "1" is given to "policy support", "numerical estimation", "Asia" and the code "14" will be given to "year".

4.2. Fixed-effect Model and Random-effect Model

Fixed-effect model and Random-effect model are both applied in the meta-analysis. Fixed-effect model assumes that all included studies investigate the same population and use the same variable and outcome definitions. A fixed-effect regression model allows for within-study variability but not study-to-study variability [37]. For comparison, random-effect can synthesize heterogeneity among study-to-study variability of the effect size [38].

In this paper, both models are employed while fixed-effect model is the benchmark, and could be specified as:

$$y_{ij} = x_{ij}\beta + \varepsilon_{ij} \text{ with } \varepsilon_i \sim N(0, {\sigma_i}^2)$$

where y_{ij} denotes the dependent variable (payback period) of observation i in study j, x_{ij} denotes a vector of dummy variables stated in Table 4, and β denotes a vector of coefficients of observation i, each of y_{ij} comes along with its associated variance ${\sigma_i}^2$.

Then, the random effect model is applied where y_{ij} is observation i from study j [39]:

$$y_{ij} = x_{ij}\beta + \mu_j + \varepsilon_{ij} \text{ with } \mu_j \sim N(\mu, \sigma_\mu^2) \text{ and } \varepsilon_{ij} \sim N(0, \sigma_\varepsilon^2)$$

where ε_{ij} denotes the standard error term and μ_j denotes the payback period random effect across the jth study

Study-Ref	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*	*25*	*26*	*27*	*28*	*29*	*30*	*31*
Technology level																							
storage tank, materials, heat transfer fluid, etc.	*	*		*		*		*												*	*		*
Evacuated tube collector				*	*			*	*	*													
Number/area of collectors	*		*		*	*	*		*								*						
Tank water temperature required							*																
Hot water consumption pattern		*					*			*					*		*			*			
Supplementary Energy Type																							
Diesel							*									*							
Gas/town gas	*							*								*		*					
LPG																*		*	*				
Electricity								*							*	*		*	*				
Natural conditions																							
Radiation		*					*	*		*		*			*	*							
Specific Region				*			*	*	*	*	*		*		*	*	*	*	*		*	*	
Policy Support		*	*					*						*	*	*		*				*	*
Methodology																							

Computer modelling/simulation		*				*		*	*	*	*						*		*	*	*		*
Experiment	*			*	*		*					*	*	*						*		*	
Numerical estimation														*									
Case study	*		*					*							*	*	*	*					
Sector																							
Residential		*	*			*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Continent																							
Asia				*		*				*		*	*	*	*	*	*	*			*		
North America											*												
South America									*														
Europe							*													*		*	*
Africa			*		*			*											*				
Oceania	*	*																					

Table 3. Independent variables and moderator variables in meta-analysis

Variables	Description	Coding of variables
Technology level		
Storage tank, materials, heat transfer fluid, etc.	Innovation, consideration, comparison or suggestion on the use of storage tank, materials, heat exchangers and so on (except solar collectors)	Dummy: 1=Focus on the storage tank, materials, heat exchangers and so on; 0=Otherwise
Evacuated tube collector	Compare with the FPCs and propose to install ETCs due to shorter payback period, or just focus on ETCs	Dummy: 1=Focus on the evacuated tube collector; 0=Otherwise
Number/area of collectors	Focus on increase the number or area of solar collectors to find out an optimization for techno-economic feasibility	Dummy: 1=Focus on the number/area of collectors; 0=Otherwise
Tank water temperature required	Analyze the impact of required tank water temperature on the techno-economic feasibility of SWHSs	Dummy: 1=Focus on the required tank water temperature; 0=Otherwise
Hot water consumption pattern	Analyze the impact of hot water consumption pattern on the techno-economic feasibility of SWHSs, such as the number of occupants or the time of use.	Dummy: 1=Focus on the hot water consumption pattern; 0=Otherwise
Supplementary Energy Type		
Diesel	Analyze the techno-economic feasibility of SWHSs with diesel as the supplementary fuel	Dummy: 1=Diesel; 0=Otherwise
Gas/town gas	Analyze with gas/town gas as the supplementary fuel	Dummy: 1=Gas/town gas; 0=Otherwise
LPG	Analyze with LPG as the supplementary fuel	Dummy: 1=LPG; 0=Otherwise
Electricity	Analyze with electricity as the supplementary energy	Dummy: 1=Electricity; 0=Otherwise
Natural conditions		
Radiation	Focus on the radiation through a year and look into its influence on the techno-economic feasibility of SWHSs	Dummy: 1=Focus on the sun radiation; 0=Otherwise
Specific Region	Focus on a specific region and assess its natural conditions on the techno-economic feasibility of SWHSs	Dummy: 1=Focus on the specific region; 0=Otherwise
Policy Support	Analyze the effective launch of SWHSs program under policy supports: incentives, subsidies, tax credit, etc.	Dummy: 1=Focus on policy support; 0=Otherwise
Methodology		
Computer modelling/simulation	Employed by the author to assist in the design, creation, and evaluation of SWHSs and make judgement on 'what if' case scenarios.	Dummy: 1=Computer modelling/simulation; 0=Otherwise
Experiment	Employed by the author to practically set up the apparatus of SWHSs and make observations on the test results.	Dummy: 1=Experiment; 0=Otherwise
Numerical estimation	Employed by the author to use assumptions and formulas to estimate the techno-economic feasibility of SWHSs	Dummy: 1=Numerical estimation; 0=Otherwise
Case study	Employed by the author to analyze the techno-economic feasibility of SWHSs while applying in a specific region	Dummy: 1=Case study; 0=Otherwise
Sector		

Residential	Analyze the techno-economic feasibility of SWHSs in the residential sector, such as domestic hot water heating, domestic space heating and cooling, etc.	Dummy: 1=Focus on residential sector; 0=Otherwise
Continent		
Asia	Specify the continent of the analyse aims to	Dummy: 1=Asia; 0=Otherwise
North America	Specify the continent of the analyse aims to	Dummy: 1=South America; 0=Otherwise
South America	Specify the continent of the analyse aims to	Dummy: 1=North America; 0=Otherwise
Europe	Specify the continent of the analyse aims to	Dummy: 1=Europe; 0=Otherwise
Africa	Specify the continent of analyse aims to	Dummy: 1=Africa; 0=Otherwise
Oceania	Specify the continent of the analyse aims to	Dummy: 1=Oceania; 0=Otherwise
Year of Study	Year of the paper publication	Continuous variable (6-17, represents paper publication from year 2006 to year 2017)

Table 4. Coding of variables

5. Discussion and Implications

The meta-analysis results are presented in Table 5. In the model regression process, we take the natural logarithm of the payback periods for two reasons: first, to eliminate potential heteroskedasticity; and second, to allow the output of coefficients to interpret the percentage of payback period change. The results of the meta-analysis in the table provide insight in the study-to-study heterogeneity. There are 16 significant meta-coefficients, with 9 negative coefficients and 7 positive coefficients. A negative coefficient indicates relatively shorter payback period estimation, whereas a positive coefficient indicates relatively longer payback period estimation. Those significant coefficients are determinants of variations in the payback period estimates across studies.

Variable	*Model 1: Fixed-effect*	*Model 2: Random-effect*
	Coefficient	Coefficient
***Dependent variable**: payback period*		
Independent variables:		
Technology level		
Storage tank, materials, heat transfer fluid, etc.	-0.656 (0.505)	-0.556 (0.495)
Evacuated tube collector	-0.827*** (0.276)	-0.842*** (0.275)
Number/area of collectors	-1.160*** (0.400)	-1.128*** (0.398)
Tank water temperature required	7.243*** (1.546)	6.908*** (1.509)
Hot water consumption pattern	0.750*** (0.243)	0.711*** (0.240)
Supplementary Energy Type		
Diesel	-0.736* (0.381)	-0.752* (0.381)
Gas/town gas	-0.161 (0.334)	-0.184 (0.343)
LPG	-0.092 (0.348)	-0.112 (0.347)
Electricity	-0.243 (0.329)	-0.270 (0.328)
Natural conditions		
Radiation	-1.480*** (0.517)	-1.358*** (0.502)

Specific Region	-0.611* (0.321)	-0.557* (0.317)
Policy Support	-2.757*** (0.887)	-2.569*** (0.866)
Methodology		
Computer modelling/simulation	3.207*** (1.070)	2.987*** (1.048)
Experiment	2.383*** (0.852)	2.211** (0.834)
Numerical estimation	-1.252*** (0.455)	-1.162** (0.446)
Case study	1.290*** (0.409)	1.233*** (0.405)
Sector		
Residential	-2.100*** (0.653)	-2.021*** (0.648)
Continent		
Asia	1.696** (0.731)	1.611** (0.726)
North America	0.209 (0.616)	0.192 (0.616)
South America	3.468*** (0.863)	3.405*** (0.861)
Europe	-1.739** (0.785)	-1.628** (0.777)
Africa	0.393 (0.593)	0.417 (0.593)
Oceania	-0.777 (0.537)	-0.739 (0.536)
Year of Study	0.235 (0.059)	0.251 (0.078)

Note: *** Significant level at 1%

** Significant level at 5%

* Significant level at 10%

Table 5. outcomes of meta-analysis

First, in the technology level category, the effects of all variables are significant on the payback period except the storage tank, materials, heat transfer fluid, etc, which reveals that the selection of collectors in SWHSs play a more important role comparing to other components. Especially the payback period decreases significantly when the type and the number/area of collectors are considered. It implies that although replacing FPCs by ETCs or increasing the number/are of collectors would cause higher upfront investment, the corresponding higher system efficiency would eventually compensate and pay off. The variables of required tank water temperature and hot water consumption pattern genuinely reflect the fact that the individual hot water usage pattern and family composition could drastically affect the payback period. Evidence could be found in the Lutz model [40], which calculates a solar collector area and payback period for households based on their daily consumption pattern (required hot water temperature, number of children, adults and seniors, seasons, pay/no-pay of the energy bills, absence of clothes washer or dishwasher, etc.). In general terms, Lutz model is consistent to our findings that increasing the required temperature and number of user increases the payback period. However, based on Lutz model, McCarter [41] presents three hot water consumption scenarios and finds that solely-two-seniors-formed household would consume the least hot water whereas induce longest payback period. It is also found that two-adults-two-children-formed household consumes the most hot water whereas benefits to a shortest payback period under the same solar fraction setting. This is a very interesting finding that draws researchers' and technologists' attention to envisage the optimal sizing of SWHSs and avoid oversizing. This is because unlike the solar PV system, the unused solar thermal energy in SWHS could not be transmitted to the grid-connected network, so the higher payback period induced by the solely-two-seniors-formed household comes largely from minimal hot water usage. It is slightly inconsistent to our findings which implies the increased area/number of solar collectors will lead to shorter payback period. The reason for this inconsistence might be that in our regression model, the area/number of solar collectors represents a macroscopic insight instead of a microscopic insight (the complicated family composition), so our findings are still valid.

Diesel, natural gas/town gas and LPG are primary energies, while electricity is a secondary energy generated from combustion or nuclear fission. When the replacement takes place, these energies are still necessary as supplements to SWHSs since solar energy is intermittent thus cannot always satisfy the user's demand through all day, or in winter. Therefore, it is noted that solar energy could not completely replace traditional energy in the near future. According to the meta-analysis results, the effect of using diesel as supplementary energy on the payback period reduction is significant while the effects of other fuels are insignificant. These results indicate that although various countries and even regions are utilising different energies as main sources to provide hot water, the economic viability and profitability are not limited to a specific energy type when SWHSs are installed to partially replace these traditional fuels. In the long run, the fluctuation of crude oil price in the international market should strengthen the crisis awareness of government and investors to enter the renewable energy market as soon as possible.

Natural conditions could inevitably influence the payback period of SWHSs, as the results show dependence of payback period on the solar radiation and specific region. It should be noted that to eliminate the ambiguity, the term "specific region" is used when the techno-economic analysis of SWHSs is conducted with an aim to assess the solar energy technology for a target area, which considers the natural conditions (seasons, climates, etc) of the whole region whereas the term "solar radiation" is summarized when the initial paper particularly mentioned it as an extremely important factor to influence the judgement of SWHSs installation. Backing to the statistics, the extent of significance is distinct between these two terms, solar radiation is highly significant while the specific region is slightly significant, which implies that solar radiation is no longer highly significant when combined to the whole picture of a specific region. Apart from solar radiation, the average temperature and precipitation over time are also influential factors in the concept of “climate”. Other useful elements for describing climate include the type and the timing of precipitation, amount of sunshine, average wind speeds and directions, number of days above freezing, weather extremes, and local geography.

Policy support would significantly trigger the reduction of payback period. Investors are flinched to invest in renewable energy technologies due to unsure market performance and unanticipated potential risks, citizens are unprepared and unaware to enter the renewable energy market due to lacked information. It can be seen from the meta-analysis results that government and authorities should be the bridge of investors and citizens, to lead them reach each other by financially and strategically encouraging both sides. In this meta-analysis, the term “policy support” includes incentives and subsidies, tax credits and third-party financing. Monetary policies are efficient to alleviate the financial burden of the capital cost and thus shrink the payback period. Incentives and subsidies could provide investors with the opportunities to show their interest in solar energy, and meanwhile lowering the market threshold for more investors to enter. Furthermore, the incentives and subsidies could also be granted on the conditions that if the enterprise could comply a high-standard specification, successful cases could be referred to Israel, Greece, China and Japan. However, direct incentives and subsidies may cause very high transaction costs, by contrast, tax credit is less risky although it does not lower the barrier for upfront payment, for example by lowering the Value-added Tax rates on solar water heating equipment and the Enterprise Income Tax for solar water heating technology investors. The third-party financing enables the third-party to get reimbursement from the subsequent energy savings after their purchase of SWHS equipment for the first party. Based on this principle, the risk of technical failure could be alleviated [42].

As for the study characteristics, all the four methodologies are found to have significant influences on the calculated payback period. Longer payback periods are found in the papers using computer modelling/simulation, experiment and case study as methodologies, whereas a shorter period is found in the paper using numerical estimation. In Table 2 and Table 3, only one paper ([23]) uses numerical estimation and it provided 27 payback period estimations. The estimations in [23] account for 24.5% of the total 110 estimations, whereas most of the estimations in other papers only account for less than 9% of the total estimations. In ref. [23], the average payback period is 7.73 years, which is below the average of all estimations (8.58 years). Therefore, this indicates that the payback period calculated using numerical estimation is shorter. By contrast, the payback periods calculated using the other three methodologies are longer, which seems reasonable as these three methodologies estimate the payback period in a more complicated and real situation. In the overview part, the residential sector and non-residential sectors are considered. In the meta-analysis, only residential sector is selected as a moderator variable to evaluate the significance to affect payback period. The meta-analysis coefficient indicates a shorter payback period if the project is enacted for residential use. In addition, the meta-analysis results of different continents illustrate wide differences. First of all, the studies in South America, Asia and Europe indicate significant influence on the analysis of payback period. One possible reason might be that these three continents possess numerous market share and global capacity regarding the solar water heating collectors, as 10 of top 12 countries in the aforementioned area are from Asia (71% in China, 1.3% in India, 0.8% in Israel and 0.6% in Japan), South America (1.9% in Brazil) and Europe (3% in Germany, 3%

in Turkey, 0.9% in Austria, 0.7% in Greece and 0.7% in Italy) [43]. Second, the payback period of SWHS in South America is the longest, followed by Asia, and the payback period of SWHS in Europe is the shortest. One possible reason is because large amount of countries in South America and Asia are under-developed, the utilisation of SWHSs are immature and the supportive policies are still lacking, so the investment revenue is unpredictable, and the related innovative technology is difficult to be implemented.

6. Conclusion

This paper conducts a systematic review and meta-analysis on the techno-economic feasibility of solar water heating system. By reviewing the recent papers in terms of techno-economic feasibility of the solar water heating system, a framework of the influential factors on the dissemination of solar water heating system is structured. Other than rooftop solar water heating system, solar heating façade and solar space heating system are tremendous and innovative utilization of SWHS. In addition to residential sector, SWHS is also applicable in agriculture and industrial sectors. The number of technical papers of SWHS are overwhelming, however the economic viability analyses are much less. This review gives the first compilation from the techno-economic perspective. This review summarizes the net present value, internal rate of return, payback period and benefit cost ratio of SWHSs by considering the influential factors, such as the proposed system, back-up fuel types, required tank water temperature and subsidy level. The review provides concrete evidence and information for meta-analysis analysis in terms of the payback period.

Meta-analysis is a technique to elaborate and synthesize separate and scattered results or evidence from different studies into a single analysis, and it is able to convert qualitative information to quantitative statistics. Before conducting meta-analysis, publication bias is checked regarding 110 estimations of payback period from 23 studies. Both funnel plot and Begg's test indicate absence of publication bias. In this paper, meta-analysis mainly employs the fixed-effect model and random-effect model, and examines the statistical significance of independent variables and moderator variables on the dependent variable. Technology level, supplementary energy type, natural conditions and policy support are considered as key factors, and the regression model in meta-analysis is moderated by several study characteristics such as the methodology, continent and study year. Results indicate 16 significant variables, including 9 negative variables (evacuated tube collector, number/area of collectors, use diesel as supplementary fuel, radiation, specific region, residential sector, numerical estimation and study conducted in Europe.) and 7 positive effects (tank water temperature required, hot water consumption pattern, computer modelling/simulation, experiment, case study, study conducted in Asia and South America). Positive and negative effects indicate a longer or shorter estimation in payback period, respectively. Implications and discussions are conducted based on the results of the meta-analysis regarding the technology aspect, supplementary fuel type, natural conditions, and solar-related supporting policies. In addition, the study variation caused by research methodology, sector, and continent are also analysed.

However, limitations remained in this paper in terms of meta-analysis. First, there could be disagreement over which variables are the important ones in the analysis. Second, when meta-analysis weights each published study equally, it risks overweighting the results of those who publish many small articles, each with a single result, compared to larger articles with a substantial number of results. Future works are suggested to figure out solutions to eliminate the limitations.

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