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Decision-making tool for the optimal selection of a domestic water-heating system considering economic, environmental and social criteria: application to Barcelona (Spain)

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Abstract

The research presented in this paper has two main objectives. First, it aims to generate an assessment tool for ranking and selecting the most sustainable domestic water-heating system (WHS) (with the lowest economic, environmental and social impact) that could be applied in any location and with any demand. Second, it aims to ascertain which WHS is the most sustainable in places with a climate and solar radiation like that of Barcelona, Spain, where a minimum solar contribution to domestic water heating is compulsory for new buildings and significant renovations. Multi-criteria decision analysis was employed to create the optimised flexible assessment tool. The Delphi method was followed to perform the surveys, and to provide the objectivity required in the identification of impacts, the definition of indicators and the assignment of weights. The most relevant criteria were determined: annual cost, material consumption, energy consumption, GHG emissions, space requirement, visual impact and occupational risks. The resulting tool was tested by analysing twelve domestic WHS, including two conventional systems, and ten combinations of five solar thermal technologies with two conventional systems as backup for a changing room in a sport centre located in Barcelona. The two conventional WHS studied were a natural gas-fired condensing boiler and an electric water heater. The five solar thermal technologies were: a flat plate with a harp design, a flat plate with a serpentine design, a heat-pipe evacuated tube, a direct-flow evacuated tube, and a direct-flow evacuated tube with CPC. The dynamic thermal simulation programme T*SOL was used to dimension the solar thermal systems. Two sensitivity analyses were carried out: one on weights and one on references. The tool proved very useful in the assessment of these systems, and could also help in decision-making processes to select the most sustainable WHS for other locations and domestic hot water demands.

Keywords: sustainability, domestic water-heating systems, solar collectors, multi-criteria decision analysis, indicators, environmental impact.

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Contents

1. Introduction

The final energy consumption of the residential sector in the European Union (EU) accounted for 26.8% of the total energy consumption in 2013. This was the highest percentage of all sectors; even slightly above that of road transport or industry [1]. Water heating was responsible for about a quarter of this energy consumption [2]. Furthermore, households accounted for 19% of greenhouse gas (GHG) emissions in the EU in 2012 [1]. Residential energy consumption in Spain accounted for 18.5% of the total energy consumption in the same country, and 5.4% of the total residential energy consumption in the EU (28 countries) in 2015 [3]. Household GHG emissions in Spain accounted for 20.4% of the total GHG emissions in the same country, and 7.5% of the total household GHG emissions in the EU in 2014 [4]. Thus, the appropriate choice of a domestic water-heating system (WHS) can largely reduce energy consumption and operational costs, and protect the environment [5].

Domestic solar water heating is a well-developed technology that is used to reduce energy consumption for domestic hot water (DHW) supply [2]. Its potential for significantly reducing domestic energy consumption is recognised [2]. Legislation on buildings is progressively introducing domestic solar WHS. Consequently, the total installed capacity is increasing every year, and reached 33.3 GWth in operation in 2015 in the EU 28 and Switzerland, which generated an estimated 23.5 TWhth of solar thermal energy while contributing to a saving of 6.3 $MtCO_2$ [6]. In the case of Spain, the total installed capacity in operation in 2015 was 2296 MWth [6].

All three pillars of sustainability, economic, social and environmental factors, must be considered in decisions on the most appropriate WHS for a given location and demand, to obtain a comprehensive view of the system. In fact, sustainability consists of finding a balance between these three dimensions, and is therefore an interdisciplinary problem. If an analysis is limited to one or two dimensions, the view of the problem will only be partial. However, in the literature review presented in the next section, few studies were found that compare types of solar collector systems including flat plates, evacuated tubes and conventional systems for producing DHW from a complete, sustainable, multi-criteria perspective that includes social, economic and environmental aspects. Further comparative studies of solar and conventional commercial WHS are needed to help policy makers, installers and users to make decisions on the most sustainable WHS [7].

The research presented in this paper has two main objectives: (1) to develop a multi-criteria decision-making tool applicable to any location and demand that enables prioritisation and selection of the best WHS, including solar and conventional systems and considering the three dimensions of sustainability, and (2) to illustrate the use of the tool with a case study and determine the best WHS to be used in a sport centre located in Barcelona, Spain.

This research extends knowledge by providing a multi-criteria tool for sustainable decision making on WHS. It is innovative as it applies multi-attribute utility theory (MAUT) to a new area: selection of the best domestic WHS. It explores the interdisciplinary connection between fields of knowledge in solar and conventional WHS. It connects engineering with economy, environment and society, in other words, it looks at engineering from the perspective of sustainability; and sustainability is fundamental for present and future generations.

According to the present study and under the studied climatic and hot water demand conditions, policies that encourage the installation of flat plate solar WHS are justified, particularly in a society that increasingly recognises the value of the environment and calls for a reduction in GHG emissions and conventional energy consumption.

The rest of the paper is organised as follows. The second section presents a literature review of research on technical, economic and environmental aspects of solar WHS and multi-criteria decision analysis (MCDA) applied to the energy sector, particularly to renewable energies and domestic solar WHS. The third section develops a decision-making tool for selecting optimal domestic WHS based on MAUT and the Delphi method. In the fourth section, a case study on determining the optimal WHS out of twelve alternatives is solved by using the proposed tool and simulations with T*SOL software. The fifth and last section of the paper presents the conclusions of the study.

2. Literature review

The definition of energy policies and the selection of the best WHS should be based on evaluating the sustainability of existing technologies, considering all three pillars of sustainability, economic, environmental and social factors, in an integrated way. However, much of the current literature on solar WHS has focused on technical, economic or environmental aspects separately.

Some previous studies on solar WHS have focused on technical and economic aspects. For example, Tian and Zhao [8] and Jamar et al. [9] reviewed solar collectors for low- and high-temperature applications in terms of optical optimisation, heat loss reduction, heat recuperation enhancement and sun-tracking mechanisms. Allouhi et al. [10] studied the technical performance of flat plate and evacuated tube collectors in several locations in Morocco. Buker and Riffat [11] reviewed the current status of building-integrated solar thermal collectors. Wang et al. [12] reviewed solar WHS in terms of technical background, market potential and research questions. Gautam et al. [13] reported studies on technical advancements, economic feasibility and the overall scenario of solar WHS. Islam et al. [14] and Shukla et al. [15] discussed the design features, energy efficiency and cost effectiveness of solar WHS. Al-Badi and Albadi [16] and Benli [17] evaluated technical and economic aspects of solar WHS in Oman and Turkey, respectively. Vieira et al. [18] concluded that split systems performed better than thermosiphon in Brisbane, Australia, in terms of energy efficiency and level of service, and hence should be prioritised in energy efficiency policies.

Additionally, several recent studies have reported on environmental and economic aspects of solar WHS. For example, Ibrahim et al. [5] qualitatively reviewed the operational costs, environmental effects and performance of existing WHS. Lamnatou et al. [19] critically reviewed the existing life-cycle analyses on building-integrated solar thermal systems. Greening and Azapagic [20] quantified the environmental impact of solar WHS in regions with low solar radiation, such as the UK, while Koroneos and Nanaki [21] quantified the environmental impact and economic performance in Thessaloniki, Greece. Shaddel and Shokouhian [22] studied the payback period and the annual reduction in natural gas consumption and CO_2 emissions due to the installation of solar thermal collectors in a multiple-dwelling complex in Mashhad, Iran. Bessa and Prado [23] assessed the reduction of CO_2 emissions with the use of solar WHS in comparison with electric showers in social housing in several Brazilian climatic zones.

Cassard et al. [24] and Friedrich Ferrer [25] analysed economic aspects of solar WHS, the former in the US and the latter in South Africa (SA). Their conclusions were similar: solar WHS are only economically attractive in a few regions. The high initial cost is a primary driver of the low penetration of residential solar WHS in the US: “the life-cycle benefits often do not greatly exceed the capital cost of the system” [24]. However, solar WHS provide other “benefits such as reduced reliance on fossil fuels and reduced carbon dioxide emissions” but these are somehow “external to the consumer and difficult to quantify” [24].

In fact, the search for a logical, optimal solution to the sustainability of energy systems is a complex process that requires robust quantitative methods [26]. In this regard, MCDA could become a powerful tool for decision making on sustainable energy systems [26, 27]. There are several studies on renewable energies and domestic solar WHS based on MCDA. Troldborg et al. [28] assessed the sustainability of eleven renewable energy technologies considering three environmental, three technical, and three socio-economic criteria using the PROMETHEE method. They considered uncertainty in the input information using a Monte Carlo simulation. As the assessment was performed at national level and hence was not specific, the uncertainty associated with the criteria and the ranking was high. They stated that the degree of uncertainty for actual site-specific projects would probably be lower. Stein [29] developed a model to rank nine renewable and non-renewable electricity production technologies considering financial, technical, environmental and socio-economic-political criteria using the analytic hierarchy process (AHP). A sensitivity analysis of the weights was performed considering four scenarios. It was concluded that solar, wind, hydropower and geothermal provide the most overall benefits and, therefore, policies to encourage the use of these type of energies should be expanded. Cavallaro [30] used the multi-criteria PROMETHEE method to rank twelve solar thermal technologies according to seven economic and technical criteria, and determined the weight stability intervals within which the weight of each criterion can be modified without changing the ranking. Nixon et al. [31] designed a new solar thermal collector using an MCDA including quality function development, the AHP and the Pugh selection matrix and sixteen technical, financial and environmental criteria.

Notwithstanding the increasing use of solar WHS, the improved technology, and the recognised environmental advantages in terms of energy consumption and GHG emissions, the overall sustainability (that covers all three pillars) of these methods in comparison with each other and in relation to conventional systems is not yet clear. Neither is it clear which is the best system from the perspective of sustainability for use in a specific location with specific demands. Comparative studies of all the main commercially available solar WHS configurations and types of solar collectors are needed [7]. In this area, Hang et al. [7] carried out a relevant study in which six types of domestic WHS including two types of solar collectors (flat plate and evacuated tube) in combination with two types of auxiliary systems (natural gas and electricity) and two conventional systems (natural gas and electricity) were evaluated from energy, economic and environmental perspectives.

3. Methods

MCDA can help to select the best of several alternatives taking into account possible conflicts between criteria, considering that the best alternative according to one criterion is not necessarily the best according to another criterion. Therefore, the best alternative overall cannot be determined directly. In this sense, the MCDA is an integrated approach that enables overall assessment, comparison, and ranking of alternatives, considering all the criteria in an integrated manner. While it is necessary to be aware of uncertainties and analyse how they may affect the result [28, 31], MCDA can be a useful technical-scientific tool for decision-making support [30, 31].

As described in Martin-Gamboa et al. [26], an increasing number of studies on energy policy and management use MCDA for energy planning and to evaluate aspects of renewable energies [29,32]. Within MCDA, the multi-attribute utility theory (MAUT) [33] is the most commonly used for assessing the sustainability of energy systems, according to Martin-Gamboa et al. [26]. MAUT was chosen for the study presented in this paper as it helps to solve discrete problems, it can be understood intuitively, and it is based on a solid foundation [34].

To improve and verify the quality and robustness of the tool generated using MAUT, several strategies and methods were followed: the Delphi method, controls in the surveys to minimise and avoid bias, and two sensitivity analyses in the case study to check the robustness of the results. These strategies are explained in the present section and in Section 4.3. Sensitivity analyses. Fig. 1 shows the steps taken to develop an Impact Index for evaluating domestic WHS, according to MAUT in combination with the Delphi method, and the application of the Impact Index to a case study.

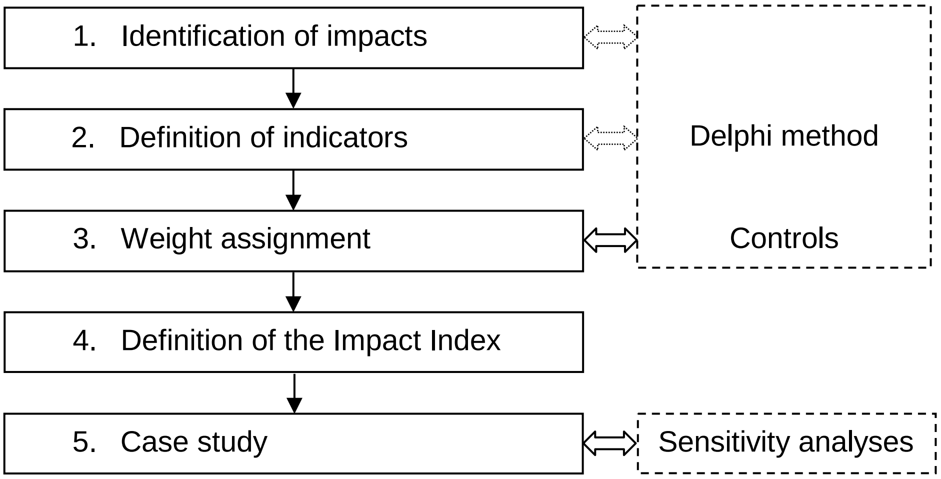


Fig. 1. The main steps used to develop the decision-making tool based on MAUT for the optimal selection of domestic WHS, and a practical application.

The Delphi method for construction and engineering management is a structured research method that can be used to obtain highly reliable data from certified experts by means of strategically designed surveys [35]. This method was used to select the experts, administer rounds of surveys, and define consensus to obtain the data required to apply the MAUT, including the identification of impacts, the definition of indicators and the weight assignment. Sixteen panellists were initially contacted to complete the surveys, following the Delphi method [35]. Thirteen responded and participated, which is more than the minimum number (8-12) recommended by Hallowell and Gambatese [35]. All the panellists met the expertise requirements of the Delphi method [35], either those of the rigorous or the flexible implementation of the method, since academic experience was not particularly relevant to the study. This results in the incorporation of highly qualified and well-rounded panellists. They were representative of stakeholders related to solar thermal systems for DHW: design, project, and management engineers and architects, including some academics.

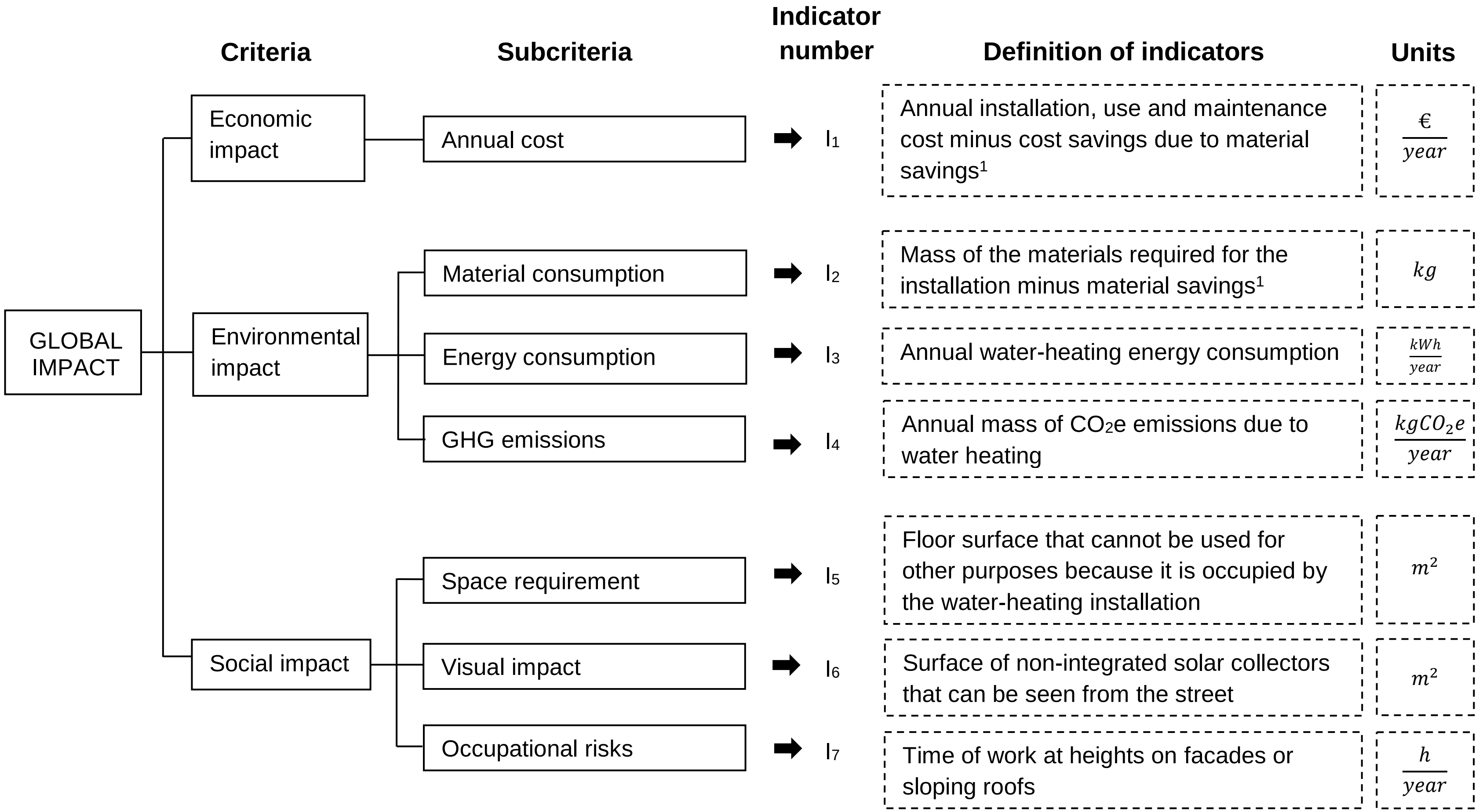
3.1. Identification of impacts

Impacts were identified based on previous and preliminary research [26, 28-30, 34, 36, 37] and adapted to the research goal according to the experts' comments in the surveys.

The study evaluated the impacts presented in Fig. 2 classified into three criteria (economic impact, environmental impact and social impact) and seven subcriteria (annual cost, material consumption, energy consumption, GHG emissions, space requirement, visual impact, and occupational risks).

3.2. Definition of indicators

According to the experts' comments, a quantitative indicator was defined for each subcriterion as presented in Fig. 2. Indicators I_1 and I_2 include the possibility of integrated solar collectors instead of some construction material. The space requirement (I_5) includes common and private space occupied by the WHS. In the case of solar collectors installed on sloping roofs or facades, there is the risks of falls to lower levels when working at heights during installation and maintenance (I_7).



Indicator number	Definition of indicators	Units
I_1	Annual installation, use and maintenance cost minus cost savings due to material savings[1]	$\frac{€}{year}$
I_2	Mass of the materials required for the installation minus material savings[1]	kg
I_3	Annual water-heating energy consumption	$\frac{kWh}{year}$
I_4	Annual mass of CO_2e emissions due to water heating	$\frac{kgCO_2e}{year}$
I_5	Floor surface that cannot be used for other purposes because it is occupied by the water-heating installation	m^2
I_6	Surface of non-integrated solar collectors that can be seen from the street	m^2
I_7	Time of work at heights on facades or sloping roofs	$\frac{h}{year}$

[1] In case of integrated collectors that replace construction materials

Fig. 2. Impacts of domestic WHS and their indicators.

3.3. Weight assignment

The weights reflect the importance of the criteria and subcriteria and, specifically in the present study, the importance of minimising the impacts. The Delphi method [35] was followed to perform the surveys and obtain the weights. Weights can be assigned using an ordinal method [30] or the analytical hierarchy process [31]. Alternatively, all the criteria can be considered to have the same importance [28], and a sensitivity analysis can be performed considering several scenarios [29]. For the analysis here, the direct assignment method [32] was used to assign weights to the criteria and subcriteria. Two rounds of surveys were enough to reach consensus on the weights.

In the first round, the panellists were provided with the diagram presented in Fig. 2 and with instructions on how to assign the weights according to the direct assignment method. Panellists were asked to respond to the following question: “If you had to choose the best solar WHS, what importance do you think should be assigned ideally in the context of a developed country?”. The only restrictions were that the sum of the weights of the criteria (economic impact, environmental impact and social impact) had to be 100, the sum of the weights of the subcriteria within environmental impact (material consumption, energy consumption and GHG emissions) had to be 100, and the sum of the weights of the subcriteria within social impact (space requirement, visual impact and occupational risks) had to be 100. The weights assigned by the panellists in the first round are presented in Table 1.

Table 1. Local weights of the criteria and subcriteria assigned by the 13 panellists in the first round of surveys and their average.

Criteria	**Subcriteria**	**Local weights (%)**													**Panellist local weights average (%)**
		Panellist													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
Economic impact	Annual cost	30	50	50	70	80	50	40	50	30	30	30	20	40	44
Environmental impact	-	35	35	20	20	10	40	50	25	35	60	20	50	30	33
	Material consumption	40	25	30	40	10	20	20	40	30	20	20	25	25	27
	Energy consumption	30	50	40	30	80	60	40	40	40	20	50	50	30	43
	GHG emissions	30	25	30	30	10	20	40	20	30	60	30	25	45	30
Social impact	-	35	15	30	10	10	10	10	25	35	10	50	30	30	23
	Space requirement	20	60	5	75	10	40	30	50	25	5	25	30	40	32
	Visual impact	30	20	60	20	80	40	10	40	25	5	25	30	20	31

	Occupational risks	50	20	35	5	10	20	60	10	50	90	50	40	40	37

The variations in the weights assigned by the experts reflect differences in their preferences, especially in a new field in which there is no established formal knowledge. For example, as expressed in their comments, some panellists think that solar WHS must be economically advantageous over conventional solutions in order to choose the solar alternative, even though they consider that solar WHS are better environmentally. Therefore, they assigned higher weights to economic impact. In contrast, some panellists think that solar WHS should be preferred to conventional solutions, despite having a higher cost, because they are more environmentally friendly. Therefore, these panellists assigned higher weights to the environmental impact.

Consequently, several rounds of surveys are needed for the experts to take into account the group’s feedback and reconsider their rationale and numerical assignments of weights, to eventually reach a consensus. According to the Delphi method [35], consensus is achieved when the median absolute deviation is <1/10 of the range of possible values for quantitative studies. As weights can adopt values between 0% and 100%, consensus will be achieved when the median absolute deviation is <10%. As recommended in Hallowell and Gambatese [35], the median absolute deviation (Equation (1)) is used instead of the standard deviation, because it measures variability from the median, which is less likely to be influenced by biased results than the mean (used for calculating the standard deviation).

$$Median\ absolute\ deviation = \frac{\sum_{i=1}^{n}|x_i - median|}{n} \tag{1}$$

Where n is the total number of data items and x_i is the data i. According to Table 2, seven out of nine criteria and subcriteria did not meet the consensus requirement and, therefore, a second round of surveys was performed.

Table 2. Median, median absolute deviation and consensus verification for the local weights of the criteria and subcriteria in the first round of surveys.

Criteria	**Subcriteria**	**Median of the local weight (%)**	**Median absolute deviation**	**Consensus (median absolute deviation <10%)**
Economic impact	Annual cost	40	13.1	No
Environmental impact	-	35	11.2	No
	Material consumption	25	6.9	Yes
	Energy consumption	40	10.8	No

	GHG emission	30	8.1	Yes
Social Impact	-	25	11.2	No
	Space requirement	30	15.8	No
	Visual impact	25	13.8	No
	Occupational risks	40	18.5	No

Hallowell and Gambatese [35] suggest providing the median response from round 1 as feedback for round 2. However, the median results do not meet the requirements for the local weights: the sum of the median of the weights of the criteria is not 100, the sum of the median of the weights of the subcriteria within environmental impact is not 100, and the sum of the median of the weight of the subcriteria within social impact is not 100. The average weights meet these requirements and, therefore, were provided instead of the median as feedback for the second round. The panellists were requested to reconsider their weight assignments taking into account the average weights from round 1 and to provide reasons if their assignments in the second round did not meet the consensus requirement. A total of six panellists described the rationale behind their assignments. Table 3 presents the resulting weights for this second round. The panellist numbers in Table 3 correspond to those in Table 1.

Table 3. Local weights of the criteria and subcriteria assigned by the 13 panellists in the second round of surveys and their average.

Criteria	**Subcritera**	**Local weights (%)**													**Panellist local weights average (%)**
		Panellist													
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	
Economic impact	Annual cost	35	45	50	50	70	50	40	50	32	35	35	30	40	43
Environmental impact	-	33	35	25	30	15	40	45	25	34	45	25	40	30	33
	Material consumption	35	25	30	37	20	20	20	35	29	25	20	25	25	26
	Energy consumption	35	45	40	30	60	50	45	40	41	35	50	50	35	43
	GHG emissions	30	30	30	33	20	30	35	25	30	40	30	25	40	31
Social impact	-	33	20	25	20	15	10	15	25	34	20	40	30	30	24
	Space requirement	25	45	10	60	33	35	30	35	30	25	25	30	40	33
	Visual impact	30	25	60	20	33	35	10	35	25	25	30	30	25	29
	Occupational risks	45	30	30	20	34	30	60	30	45	50	45	40	35	38

As can be seen in Table 4, in this second round, all the criterion and subcriterion weights meet the consensus requirement. Therefore, consensus was reached, and the weights assigned in the second round are the proposed weights for the method. The local weights for criteria and subcriteria and the global weights are presented in Table 5. These are the resulting reference weights for the tool developed in this study. They can be used to evaluate domestic WHS and can be adjusted to the specific conditions of the case under evaluation.

The following controls were implemented during the two rounds of surveys to minimise and avoid bias [35]:

- Question order was randomised for each panel member and each round to reduce the contrast and primacy effect.
- Panel members were anonymous to avoid the dominance effect.
- Means were reported as feedback for the second round to minimise contrast, Von Restorff, recency and primacy effects, and myside bias.

Reasons for the panellists' weight assignments were going to be provided as feedback in the third round of surveys as indicated in the Delphi method [35], but consensus was already reached in the second round.

Table 4. Median, median absolute deviation and verification of the consensus criterion for the local weights of the criteria and subcriteria in the second round of surveys.

Criteria	**Subcriteria**	**Median of the local weight (%)**	**Median absolute deviation**	**Consensus (median absolute deviation <10%)**
Economic impact	Annual cost	40	8.3	Yes
Environmental impact	-	33	6.8	Yes
	Material consumption	25	4.7	Yes
	Energy consumption	41	6.5	Yes
	GHG emissions	30	3.7	Yes
Social Impact	-	25	7.0	Yes
	Space requirement	30	7.9	Yes
	Visual impact	30	7.2	Yes
	Occupational risks	35	8.5	Yes

Table 5. Reference weights assigned by the experts to the impacts of domestic WHS.

Criteria	**Local weights for criteria**	**Subcriteria**	**Local weights for**	**Global weights (%)**

	(%)		subcriteria (%)	
Economic impact	43	Annual cost	100	43
Environmental impact	33	Material consumption	26	9
		Energy consumption	43	14
		GHG emissions	31	10
Social impact	24	Space requirement	33	8
		Visual impact	29	7
		Occupational risks	38	9
Total	100	-	-	100

Economic impact (43%) is considered the most important criterion in choosing the best domestic WHS. Minimisation of environmental impact is considered the second most important criterion (33%). The least important criterion is social impact (24%). Within the environmental impact criterion, the experts consider that minimisation of energy consumption is the most important subcriterion followed by the minimisation of GHG emissions. Material consumption is considered the least important subcriterion within environmental impact. Within social impact, the most important subcriterion is occupational risks, closely followed by space requirement and, finally, visual impact.

3.4. Definition of the Impact Index

The Impact Index (II_i) of the i domestic WHS (an alternative) is defined in Equation (1), according to the additive form of the multi-attribute utility function of Keeney and Raiffa [33], but with an impact approach instead of a value approach. The best alternative is the one with the lowest Impact Index.

$$II_i = \sum_j w_j \cdot Impact_{ij} \tag{1}$$

Where w_j is the global importance or weight assigned to the j subcriterion from Fig. 2. The values presented in Table 5 can be referred to. The $Impact_{ij}$ is the relative impact produced by the i alternative for the j subcriterion. The $Impact_{ij}$ can be defined as presented in Equation (2), using the alternative with the greatest impact for each subcriterion as a reference.

$$Impact_{ij} = \frac{I_{ij}}{max\,\{I_{ij}\}_{j=ct.}} \tag{2}$$

Where I_{ij} is the measurement of the j indicator of the i alternative and $max\,\{I_{ij}\}_{j=ct.}$ is the maximum measurement of the j indicator among all the alternatives considered. The relative impact can, thus, adopt values between 0 and 1. Alternatively, the $Impact_{ij}$ can be defined using an alternative as a reference, as presented in Equation (3).

$$Impact_{ij} = \frac{I_{ij}}{I_{refj}} \tag{3}$$

Where I_{refj} is the measurement of the j indicator for the alternative taken as a reference. The impact of the alternatives is compared with the impact of a real alternative. The alternative taken as a reference generates a relative impact equal to 1 and the remaining alternatives, a proportionate impact, that is higher or lower than 1. Equation (3) can be applied when there is at least one alternative that produces all the impact types generated by the other alternatives, and that alternative would be the one taken as a reference. Otherwise, if one measurement of the reference alternative were 0, according to Equation (3), the relative impact of the rest of the alternatives would be infinite. All the relative impacts of all the alternatives must be calculated using the same equation, either (2) or (3), so that the alternatives can be compared.

4. Case study

4.1. Introduction

A case-study approach was used to illustrate the practical use of the method. The method was used to compare twelve domestic WHS including combinations of two conventional and five solar thermal systems for a changing room designed for 100 people in Barcelona, Spain. Three pieces of legislation are applicable [38]: national laws of the Spanish government [39]; regional laws of the Catalan government [40], and local laws of Barcelona City Council [41]. The three legislative acts establish the DHW demand at a reference temperature of 60º per person per day for different uses, as presented in Table 6 for a changing room. They also establish the annual minimum solar contribution to DHW, depending on the daily DHW demand and the climatic zone (I, II, III, IV and V), which, in turn, depends on the annual daily average solar radiation. According to Sancho et al. [42], Barcelona has annual average solar radiation of 4.56 kWh/m^2, which corresponds with climatic zone III. For this climatic zone and the DHW demands, the Spanish, Catalan and Barcelona legislation establish 40%, 50% and 60% of annual minimum solar contribution respectively. Considering the DHW demand and the annual minimum solar contribution, the Catalan requirements are the most demanding (1000 litres per day). Therefore, meeting the Catalan legislative requirements means fulfilling the three legislations.

Table 6. DHW demand at a reference temperature of 60º and annual minimum solar contribution for a changing room designed for 100 people in climatic zone III according to the three applicable legislative acts.

Legislation	**DHW demand at a reference temperature of 60º**		**Annual minimum solar contribution**	
	(l/day·person)	**(l/day)**	**(%)**	**(l/day)**
Spanish	21	2100	40	840
Catalan	20	2000	50	**1000**
Local from Barcelona	15	1500	60	900

The use of the Joule effect (electric water heater) as a support system for the solar thermal domestic WHS system is penalised in the regional and local legislation by demanding a higher annual minimum solar contribution (70% and 63% respectively). However, alternatives must be similar if they are to be compared. Therefore, for this study, all the alternatives with a solar thermal contribution were calculated with a solar contribution of 50% (1000 l/day), whether supported by natural gas or the Joule effect.

The domestic solar WHS studied were: two types of flat plate and three types of evacuated tube in combination with two types of conventional energy as a backup system, plus two types of conventional energy alone. Hence, there were a total of twelve alternatives, as presented in Fig. 3. Current legislation does not allow conventional energy alone for domestic water heating in new buildings, but such systems are still widely used in old buildings and including them in the comparison is interesting. Fig. 4 and 5 present the configuration of the domestic solar WHS with a natural gas-fired condensing boiler and an electric water heater respectively as the backup system considered in this study.

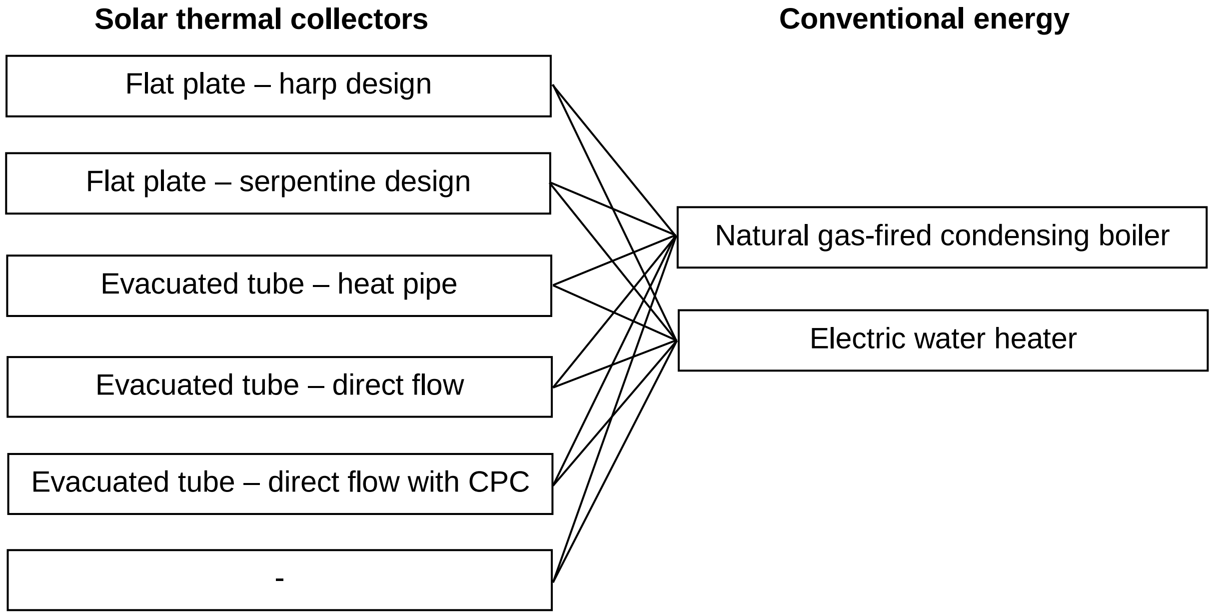


Fig. 3. Solar thermal collectors in combination with conventional energy as a backup and conventional energy alone for domestic water heating, as analysed in this study.

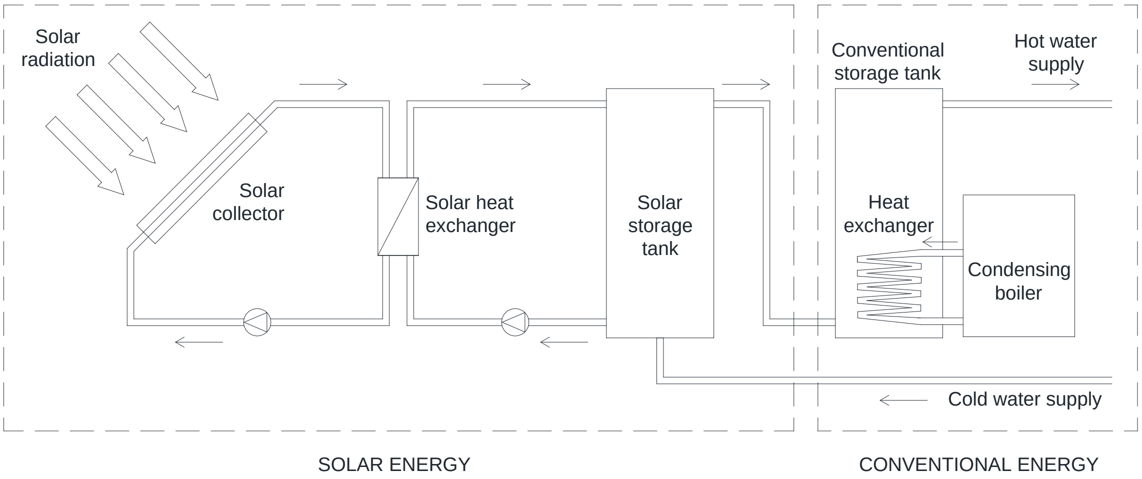


Fig. 4. Schematic diagram of the solar WHS with a natural-gas condensing boiler as a backup considered in this study.

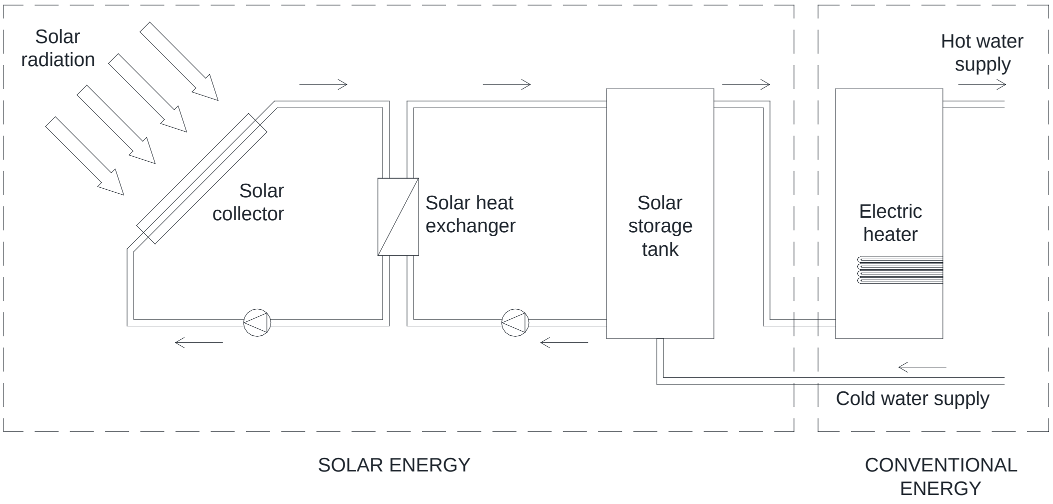


Fig. 5. Schematic diagram of the solar WHS with an electric water heater as a backup considered in this study.

The backup system must be dimensioned to cover the peak demand of DHW even if there is a solar thermal system. Therefore, the power of the natural gas-fired condensing boiler should be the same whether it works alone or as the backup for the solar thermal system. The same applies to the electric water heater.

T*SOL (www.valentin-software.com), a dynamic thermal simulation programme, was used to dimension the five solar thermal systems in Fig. 3, considering the annual cycle of solar radiation and the hourly DHW demand of the changing room. The input data for the programme of the five solar thermal systems was obtained from current commercial systems. The most relevant of these data are presented in Table 7. The solar hot water storage tank was designed with a capacity of 2000 litres, and the DHW storage tank, 1000 litres. The power needed for the condensing boiler or electric water heater is 35 kW.

Table 7. Data on the solar collectors used as input for the T*SOL simulation programme.

	Flat plate		**Evacuated tube**		
Input data	**Harp**	**Serpentine**	**Heat pipe**	**Direct flow**	**Direct flow with CPC**
Tilt angle[1]	45º	45º	25º	25º	25º
Gross area (m^2)	2.51	2.51	4.62	4.15	2.9
Aperture area (m^2)	2.4	2.37	3.19	3.22	2.57
Optical efficiency (%)	76.5	81.2	76.1	76.8	64.4

Thermal loss correction value k_1 ($W/m^2 \cdot K$)	3.653	3.478	1.047	1.36	0.749
Thermal loss correction value k_2 ($W/m^2 \cdot K^2$)	0.012	0.018	0.007	0.0053	0.005
Dimensions (mm)	2187x1147x87	2187x1147x87	2241x2061x150	2125x1954x134	2057x1390x101
Price (€)	657	727	2919	2627	1625

[1] The tilt angles of the evacuated tubes are the closest to Barcelona latitude that can be achieved with the internal tilt angle of the tube.

4.2. Results

The main results of the simulation with T*SOL are presented in Table 8. As can be seen, the systems have a similar solar contribution, as this was a requirement of the legislation, but they have different surface occupation and cost. The total energy consumption including solar and conventional energy amounts to 41267 kWh/year.

Table 8. Output data of the T*SOL simulation programme.

Output data	**Flat plate**		**Evacuated tube**		
	Harp	**Serpentine**	**Heat pipe**	**Direct flow**	**Direct flow with CPC**
Nº of collectors needed	11	10	7	7	9
Total aperture area (m^2)	26.4	23.7	22.3	22.5	23.1
Floor surface occupied by the solar collectors (m^2)	20 (in a row)	17 (in a row)	50	45	40
Solar contribution (%)	51.51	50.61	52.52	52.22	52.93
System efficiency (%)	47.4	51.6	56.1	55.4	47.1
Consumption of conventional energy (kWh)	20027	20397	19565	19741	19401
Cost of the solar collectors (€)	7227	7270	20433	18389	14625

Table 9 presents data used to calculate the indicator of annual cost (I_1). The installation cost includes the solar collectors and the rest of the elements of the solar WHS in addition to the conventional system. All the installation and maintenance costs were either obtained from current catalogues of real products or reported by professionals from the sector. To calculate the annual cost, a lifetime of 20 years was considered for the solar collectors, and 10 years for the rest of the elements. The use costs for the natural gas systems were calculated with the following gas tariff obtained from a gas company operating in Spain in 2016: a fixed part of the price of 54.22 €/month, and a part of the price depending on the gas consumption of 0.037731 €/kWh plus a special tax on hydrocarbons of 0.00234 €/kWh. The use costs for electricity consumption were calculated according to the time-of-use tariffs obtained from an electricity company operating in Spain for a contracted power of more than 15 kW as indicated in Table 10, plus a special tax on electricity of 0.051127 €/€ of the contracted power and energy consumption costs. As more precise data for calculating the electricity costs were lacking, the electricity consumption profile was assumed to be the same as the demand profile for a changing room used in the T*SOL simulation programme. VAT was not included in any of the costs in Tables 9 and 10.

Table 9. Installation, use, maintenance and total costs for the domestic WHS.

	Conventional only		Solar + natural gas-fired condensing boiler					Solar + electric water heater				
			Flat plate		Evacuated tube			Flat plate		Evacuated tube		
Cost	Natural gas-fired condensing boiler	Electric water heater	Harp	Serpentine	Heat pipe	Direct flow	Direct flow with CPC	Harp	Serpentine	Heat pipe	Direct flow	Direct flow with CPC
Installation (€)	15078	13569	26625	26668	39831	37787	34023	25116	25159	38322	36278	32514
Annual installation (€/year)	1507.80	1356.90	2301.15	2303.3	2961.45	2859.25	2671.05	2150.25	2152.4	2810.55	2708.35	2520.15
Annual use (€/year)	2304.24	7611.16	1453.16	1467.96	1434.64	1441.68	1428.06	4075.65	4116.28	4022.99	4042.34	4004.97
Annual maintenance (€/year)	60	10	1302.45	1189.5	1515.3	1367.25	1234.5	1252.45	1139.5	1465.3	1317.25	1184.5
Total annual (€/year)	3872.04	8978.06	5056.76	4960.76	5911.39	5668.18	5333.61	7478.35	7408.18	8298.84	8067.94	7709.62

Table 10. Time-of-use periods and tariffs for electricity considered in the case study.

Tariff periods and tariff concepts	**Period**		
	Peak	**Mid peak**	**Off peak**
Summer	11-15 h	8-11 h and 15-24 h	0-8 h
Winter	18-22 h	8-18 h and 22-24 h	0-8 h
Contracted power (€/kW/month)	3.394071	2.036455	1.357616
Energy consumption (€/kWh)	0.125362	0.106022	0.08082

As can be seen from Table 9, the installation costs are much higher for the solar WHS than for the conventional systems. This is because solar WHS require the same investment as conventional systems, plus the investment in the solar part of the system. The annual use costs, i.e. costs due to conventional energy consumption, are much lower for the solar WHS, due to the savings on conventional energy consumption. The annual maintenance is much higher for solar WHS than for conventional systems, due to the maintenance costs of solar WHS (considered to be 45 €/m^2/year). Regarding the total annual costs, the natural gas WHS is the most economical, followed by the solar WHS with natural gas as the backup system, then the solar WHS with an electric heater as the backup. Finally, the electric heater is the most expensive due to the high electricity costs. Therefore, using a natural gas-fired backup system is more economical than using an electric heater. This result is in agreement with Zainine et al. [43] in Tunisia. Even with reduced use costs due to energy savings, the solar WHS have higher total annual costs than the natural gas WHS, due to the higher initial investment in installation and maintenance costs.

Within the solar WHS, flat-plate collectors have lower installation costs than evacuated-tube collectors. Regarding the annual use cost, all solar WHS with natural gas as a backup are very similar, because they have a very similar solar contribution (Table 8). The same applies to the various solar collectors with an electric heater as a backup. Regarding the total annual costs of the solar collectors with natural gas as a backup, the serpentine flat plate system is the most economical, closely followed by the harp flat plate, then the direct flow with CPC, direct flow and, finally, the heat pipe. As expected, the same ranking applies to the total annual costs of the various solar WHS with an electric heater.

Table 11 presents the results of the indicators of Fig. 2 for the twelve WHS studied resulting from the combinations shown in Fig. 3. The annual cost (I_1) includes the installation, use and maintenance costs. The material consumption indicator (I_2) includes the materials from which the WHS is made. The annual energy (I_3) and CO_2 emissions (I_4) include the use stage. The CO_2 emissions have been calculated using the following factors: 0.357 and 0.252 $kgCO_2$ per kWh of final energy for electricity and natural gas respectively, according to the Spanish Government [44]. The floor space used (I_5) includes the space occupied by the WHS including the backup system, if any. None of the WHS can be seen from the street, resulting in no visual impact. Likewise, none of the studied alternatives are located on facades or sloping roofs. Therefore, none of them present risk of falls to lower levels during installation and maintenance operations. Therefore, the visual impact (I_6) and occupational risks (I_7) are not included in the subsequent stages of the analysis. The global weights of these subcriteria have been redistributed among the rest of the subcriteria (the subcriteria that are relevant to the comparison), so that the sum of their global weights is 100. They are presented in Table 12. Table 12 also presents the relative impacts and the Impact Index using Equation (2), which takes as a reference the worst result of the twelve alternatives for each indicator.

Table 11. Indicators of the impact caused by the twelve domestic WHS analysed in this study.

		Conventional		Solar + natural gas-fired condensing boiler					Solar + electric water heater				
				Flat plate		Evacuated tube			Flat plate		Evacuated tube		
Subcriteria	Indicator	Natural gas	Electric water heater	Harp	Serpentine	Heat pipe	Direct flow	Direct flow with CPC	Harp	Serpentine	Heat pipe	Direct flow	Direct flow with CPC
Annual cost (€/year)	I_1	3872.04	8978.06	5056.76	4960.76	5911.39	5668.18	5333.61	7478.35	7408.18	8298.84	8067.94	7709.62
Material consumption (kg)	I_2	268	230	1249	1235	1318	1318	1161	1211	1197	1280	1280	1123
Energy consumption (kWh/year)	I_3	41267	41267	20027	20397	19565	19741	19401	20027	20397	19565	19741	19401
CO_2 emissions (kgCO_2e/year)	I_4	10399	14732	5047	5140	4930	4975	4889	7150	7282	6985	7048	6926
Floor space used (m^2)	I_5	1.04	0.90	22.94	19.94	52.94	47.94	42.94	22.80	19.80	52.80	47.80	42.80
Visual impact (m^2)	I_6	0	0	0	0	0	0	0	0	0	0	0	0
Occupational risks (h/year)	I_7	0	0	0	0	0	0	0	0	0	0	0	0

Table 12. Relative impacts and Impact Indexes for the twelve alternatives calculated using Equation (2), and their ranking.

		Conventional		**Solar + natural gas-fired condensing boiler**					**Solar + electric water heater**				
				Flat plate		**Evacuated tube**			**Flat plate**		**Evacuated tube**		
Subcriteria	**Global weights (%)**	**Natural gas**	**Electric water heater**	**Harp**	**Serpentine**	**Heat pipe**	**Direct flow**	**Direct flow with CPC**	**Harp**	**Serpentine**	**Heat pipe**	**Direct flow**	**Direct flow with CPC**
Annual cost	51.2	0.431	1.000	0.563	0.553	0.658	0.631	0.594	0.833	0.825	0.924	0.899	0.859
Material consumption	10.7	0.203	0.175	0.948	0.937	1.000	1.000	0.881	0.919	0.908	0.971	0.971	0.852
Energy consumption	16.7	1.000	1.000	0.485	0.494	0.474	0.478	0.470	0.485	0.494	0.474	0.478	0.470
CO_2 emissions	11.9	0.706	1.000	0.343	0.349	0.335	0.338	0.332	0.485	0.494	0.474	0.478	0.470
Floor space used	9.5	0.020	0.017	0.433	0.377	1.000	0.906	0.811	0.431	0.374	0.997	0.903	0.808
Impact Index	-	0.495	0.818	0.553	0.543	0.658	0.636	0.593	0.704	0.697	0.808	0.787	0.742
Ranking	-	1	12	3	2	6	5	4	8	7	11	10	9

According to Tables 11 and 12, conventional WHS consume the least material. Within the solar WHS, the direct flow with the CPC system consumes the least material, followed by the serpentine flat plate and harp flat plate and, finally, the direct flow and heat pipe for both the solar WHS with a natural gas-fired condensing boiler as a backup and the solar WHS with an electric water heater as a backup. Regarding energy consumption, all solar WHS consume less than a half of the energy consumed by conventional WHS, as that is a requirement of the legislation. Regarding CO_2 emissions, the solar WHS with natural gas as a backup produce less than half the emissions of the natural gas WHS, and the same applies to the solar WHS with electric water heater in comparison with the electric WHS. Within solar WHS with natural gas as a backup and solar WHS with an electric water heater as a backup, the emissions are very similar due to the initial requirement of a minimum of 50% solar contribution. Conventional WHS require much less floor space than solar ones.

Considering all the impacts and their assigned relative importance, the best alternative is the natural gas WHS with an impact of 0.495. It is closely followed by the flat plate with serpentine design WHS and natural gas as a backup, with an impact of 0.543 (4.8% higher than the best system). Following this are the flat plate with harp design, the direct-flow evacuated tube with CPC, the direct-flow evacuated tube and the heat-pipe evacuated tube, all of them with natural gas as a backup. The previous ranking is repeated within the solar WHS with an electric water heater as a backup. The electric WHS has the highest global impact. The best choices for a solar WHS are serpentine and harp flat plates, which agrees with the results of Hang et al. [7].

4.3. Sensitivity analyses

4.3.1. Sensitivity analysis of the weights

The proximity in the ranking between the two best alternatives suggests that a variation in the weights could produce a variation in the ranking. A sensitivity analysis was carried out to determine the stability of the results when the weights were changed. As the solar WHS are environmentally better in terms of energy consumption and CO_2 emissions, the analysis tried to answer the following question: How much importance should society assign to the environmental factors so that the solar WHS are better overall, despite being more expensive, using more space and materials? To answer this question, the structured analysis presented in Table 13 was performed. The sensitivity analysis (1) corresponds to a reduction of 10% in the weight of the annual cost and the redistribution of this 10% between the rest of the subcriteria, keeping the previous proportionality between them. This corresponds to set weight (1a). If, with set weight (1a), there is no change in the ranking between conventional WHS and solar WHS, as is the case, the analysis continues with set weight (1b) with an additional reduction of 10% in the weight of the annual cost. The sensitivity analysis (1') is the same as in (1), except for the weight redistribution, which is only between the two subcriteria that are favourable to solar systems: energy consumption and CO_2 emissions. Analogue explanations apply to the rest of the sensitivity analyses (2)-(7) and (2')-(6'). The sensitivity analysis (8) corresponds to an increment in the weights of energy consumption and CO_2 emissions, and this increment is redistributed between the rest of the subcriteria.

Table 14 presents the resulting weights of the sensitivity analysis for which there is a change in priorities, i.e. at least one solar WHS appears to be as good as or better than the conventional WHS. The exception is the sensitivity analysis (2b), in which the weight of the subcriterion space requirement is null and the impact of natural gas WHS is 0.015 lower than serpentine WHS with natural gas. When the difference between impacts is lower than 0.010 impact units, both impacts are considered to be equal. Tables 15 and 16 present, respectively, the Impact Index and the rank obtained for the twelve alternatives for the different weight sets.

Table 13. Sensitivity analysis name (number between parentheses) according to the subcriteria with intentionally modified weights and their incremental modification (percentage between parentheses) and to the weight redistribution.

Weight redistribution	Subcriteria whose weights were intentionally modified in the sensitivity analysis and their incremental modification							
	Annual cost (-10%)	Floor space used (-5%)	Material consumption (-5%)	Annual cost (-10%) and floor space used (-5%)	Annual cost (-10%) and material consumption (-5%)	Floor space used (-5%) and material consumption (-5%)	Annual cost (-10%), floor space used (-5%) and material consumption (-5%)	Energy consumption (+5%) and CO_2 emissions (+5%)
between the rest of the subcriteria	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
between the subcriteria favourable to solar systems (energy consumption and CO_2 emissions)	(1')	(2')	(3')	(4')	(5')	(6')		-

Table 14. Weight sets which lead to a priority change (except for weight set (2b)).

Subcriteria	Weight sets for the sensitivity analysis (%)														
	original	(1c)	(1'a)	(2b)	(2'a)	(3a)	(3'a)	(4a)	(4'a)	(5a)	(5'a)	(6a)	(6'a)	(7a)	(8a)
Annual cost	51.2	21.2	41.2	56.6	51.2	54.1	51.2	41.2	41.2	41.2	41.2	57.6	51.2	41.2	44
Material consumption	10.7	17.3	10.7	11.8	10.7	5.7	5.7	14.8	10.7	5.7	5.7	5.7	5.7	5.7	9.2
Energy consumption	16.7	27.0	22.5	18.5	19.6	17.6	19.6	23.1	25.5	23.3	25.5	18.8	22.5	28.4	21.7
CO_2 emissions	11.9	19.2	16.1	13.1	14.0	12.6	14.0	16.4	18.1	16.6	18.1	13.4	16.1	20.2	16.9
Floor space used	9.5	15.3	9.5	0.0	4.5	10.0	9.5	4.5	4.5	13.2	9.5	4.5	4.5	4.5	8.2

Table 15. Impact Index of the twelve alternatives obtained for the different weight sets.

Domestic WHS			Weight sets for the sensitivity analysis														
			original	(1c)	(1'a)	(2b)	(2'a)	(3a)	(3'a)	(4a)	(4'a)	(5a)	(5'a)	(6a)	(6'a)	(7a)	(8a)
Convent.		Natural gas	0.495	0.535	0.540	0.546	0.538	0.512	0.529	0.555	0.583	0.542	0.574	0.543	0.572	0.617	0.546
		Electric water heater	0.818	0.707	0.818	0.903	0.867	0.855	0.860	0.834	0.867	0.823	0.860	0.909	0.909	0.909	0.843
Solar + natural gas-fired condensing boiler	Flat plate	Harp	0.553	0.546	0.539	0.565	0.552	0.531	0.527	0.560	0.539	0.513	0.513	0.535	0.526	0.513	0.534
		Serpentine	0.543	0.537	0.531	0.560	0.546	0.521	0.518	0.555	0.534	0.504	0.506	0.528	0.521	0.509	0.526
	Evacuated tube	Heat pipe	0.658	0.658	0.634	0.622	0.629	0.639	0.629	0.629	0.605	0.626	0.605	0.615	0.600	0.576	0.623
		Direct flow	0.636	0.639	0.615	0.608	0.612	0.616	0.607	0.615	0.591	0.604	0.586	0.597	0.583	0.562	0.605
		Direct flow with CPC	0.593	0.593	0.575	0.571	0.574	0.577	0.570	0.575	0.555	0.567	0.552	0.562	0.550	0.532	0.567
Solar + electric water heater	Flat plate	Harp	0.704	0.626	0.670	0.733	0.707	0.693	0.683	0.690	0.672	0.646	0.648	0.708	0.686	0.651	0.674
		Serpentine	0.697	0.618	0.663	0.730	0.703	0.685	0.676	0.686	0.669	0.638	0.643	0.703	0.682	0.649	0.668
	Evacuated tube	Heat pipe	0.808	0.736	0.763	0.788	0.781	0.798	0.783	0.757	0.736	0.757	0.738	0.785	0.757	0.711	0.761
		Direct flow	0.787	0.718	0.745	0.774	0.765	0.776	0.762	0.744	0.723	0.736	0.720	0.768	0.741	0.699	0.743
		Direct flow with CPC	0.742	0.670	0.703	0.735	0.725	0.736	0.723	0.702	0.686	0.697	0.684	0.731	0.706	0.667	0.704

Table 16. Ranking of the twelve alternatives according to the Impact Index obtained for the different weight sets.

Domestic WHS			Weight sets for the sensitivity analysis														
			original	(1c)	(1'a)	(2b)	(2'a)	(3a)	(3'a)	(4a)	(4'a)	(5a)	(5'a)	(6a)	(6'a)	(7a)	(8a)
Convent.		Natural gas	1	1*	3*	1	1*	1*	3*	2*	4	3	4	3*	4	6	3
		Electric water heater	12	10	12	12	12	12	12	12	12	12	12	12	12	12	12
Solar + natural gas-fired condensing boiler	Flat plate	Harp	3*	3*	2*	3*	3*	3*	2*	3*	2*	2*	2*	2*	2*	2*	2*
		Serpentine	2*	2*	1*	2*	2*	2*	1*	1*	1*	1*	1*	1*	1*	1*	1*
	Evacuated tube	Heat pipe	6	8	6	6	6	6	6	6	6	6	6	6	6	5	6
		Direct flow	5	7	5	5	5	5	5	5	5	5	5	5	5	4	5
		Direct flow with CPC	4	4	4	4	4	4	4	4	3	4	3	4	3	3	4
Solar + electric water heater	Flat plate	Harp	8	6	8	8	8	8	8	8	8	8	8	8	8	8	8
		Serpentine	7	5	7	7	7	7	7	7	7	7	7	7	7	7	7
	Evacuated tube	Heat pipe	11	12	11	11	11	11	11	11	11	11	11	11	11	11	11
		Direct flow	10	11	10	10	10	10	10	10	10	10	10	10	10	10	10
		Direct flow with CPC	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9

* When the difference between the first and second position and second and third position is less than 0.01 impact units.

As can be deduced from the tables, with slight changes in the importance of the criteria (weights assigned), solar WHS appear to be overall as good as or better than conventional WHS in 13 out of 14 cases due to their reduced energy consumption and GHG emissions, despite being more expensive, occupying more space and using more materials. This result was achieved with the weight sets presented in Table 14, with the exception of weight set (2b). For example, by reducing the importance assigned to the annual cost by 10%, or to the floor space used by 5%, or to the material consumption by

5% and redistributing it to the criteria energy consumption and GHG emissions (weight sets (1'a), (2'a) and (3'a) respectively), the serpentine WHS with gas as a backup becomes better than conventional WHS. By increasing by 5% the importance assigned to the minimisation of energy consumption and by another 5% the reduction of GHG emissions (weight set (8a)), serpentine and harp flat plate WHS with natural gas as a backup become better than conventional WHS.

The sensitivity analysis of the weights demonstrates that, for Barcelona and cities with similar climate and solar radiation, and 50% of the DHW demand supplied by solar collectors, with slight changes in weights leading to an increase in the importance of the reduction of energy consumption and GHG emissions, some solar WHS become better than the conventional WHS overall. Another interesting finding is that flat plate collectors (harp and serpentine design) rank better than evacuated tube collectors (direct flow, heat pipe and direct flow with CPC) for the 15 weight sets considered in the sensitivity analysis for both backup systems for the studied location and demand.

4.3.2. Sensitivity analysis of the reference

Another variable that may affect the results is the reference used to calculate the impact, i.e. whether Equation (2) or (3) is used, and, if Equation (3) is used, which alternative is chosen as a reference. This kind of sensitivity analysis in the present study advances knowledge, because it is very rarely performed. For the present case study, thirteen references are possible: the alternative with the greatest impact for each subcriterion when Equation (2) is used and one of the twelve alternatives when Equation (3) is used. Tables 17 and 18 present, respectively, the Impact Index and the rank obtained for the twelve alternatives using the different references. The weights presented in Table 12, assigned by the experts and normalised according to the criteria relevant to the case study, were used for this sensitivity analysis.

Table 17. Impact Index of the twelve alternatives obtained using Equation (2) and Equation (3) with the alternatives as a reference.

Domestic WHS			Name of the alternative	Reference used												
				Equation (2)	Equation (3)											
					A	B	C	D	E	F	G	H	I	J	K	L
Convent.		Natural gas	A	0.495	1.000	0.706	1.009	1.006	0.971	0.962	1.007	0.810	0.804	0.795	0.793	0.819
		Electric water heater	B	0.818	1.697	1.000	1.624	1.630	1.533	1.506	1.599	1.228	1.224	1.189	1.178	1.228
Solar + natural	Flat	Harp	C	0.553	3.396	3.406	1.000	1.020	0.894	0.873	0.947	0.803	0.818	0.726	0.715	0.765
		Serpentine	D	0.543	3.107	3.080	0.982	1.000	0.883	0.864	0.935	0.787	0.800	0.717	0.707	0.755
	Eva	Heat pipe	F	0.658	6.267	6.641	1.210	1.251	1.029	1.000	1.094	0.987	1.021	0.839	0.821	0.889

		Direct flow	E	0.636	5.781	6.102	1.167	1.204	1.000	0.973	1.063	0.952	0.983	0.816	0.799	0.864
		Direct flow with CPC	G	0.593	5.216	5.482	1.094	1.128	0.942	0.917	1.000	0.890	0.917	0.768	0.752	0.811
Solar + electric water heater	Flat plate	Harp	H	0.704	3.713	3.528	1.291	1.315	1.159	1.130	1.226	1.000	1.015	0.911	0.896	0.958
		Serpentine	I	0.697	3.427	3.205	1.276	1.298	1.152	1.124	1.218	0.987	1.000	0.905	0.891	0.951
	Evacuated tube	Heat pipe	K	0.808	6.579	6.762	1.496	1.541	1.291	1.253	1.370	1.181	1.216	1.022	1.000	1.079
		Direct flow	J	0.787	6.094	6.224	1.455	1.496	1.263	1.227	1.340	1.147	1.178	1.000	0.979	1.055
		Direct flow with CPC	L	0.742	5.525	5.601	1.379	1.416	1.202	1.168	1.274	1.082	1.111	0.949	0.930	1.000

Table 18. Ranking of the twelve alternatives obtained using Equation (2) and Equation (3) with the alternative as a reference.

Domestic WHS			Name of the alternative	Reference used												
				Equation (2)	Equation (3)											
					A	B	C	D	E	F	G	H	I	J	K	L
Convent.		Natural gas	A	1	1	1	3	2	4	4	4	3	2	4	4	4
		Electric water heater	B	12	2	2	12	12	12	12	12	12	12	12	12	12
Solar + natural gas-fired condensing boiler	Flat plate	Harp	C	3	4	5	2	3	2	2	2	2	3	2	2	2
		Serpentine	D	2	3	3	1	1	1	1	1	1	1	1	1	1
	Evacuated tube	Heat pipe	F	6	11	11	6	6	6	6	6	7	8	6	6	6
		Direct flow	E	5	9	9	5	5	5	5	5	5	5	5	5	5
		Direct flow with CPC	G	4	7	7	4	4	3	3	3	4	4	3	3	3
Solar + electric water heater	Flat plate	Harp	H	8	6	6	8	8	8	8	8	8	7	8	8	8
		Serpentine	I	7	5	4	7	7	7	7	7	6	6	7	7	7
	Evacuated tube	Heat pipe	K	11	12	12	11	11	11	11	11	11	11	11	11	11
		Direct flow	J	10	10	10	10	10	10	10	10	10	10	10	10	10
		Direct flow with CPC	L	9	8	8	9	9	9	9	9	9	9	9	9	9

As can be seen from Tables 17 and 18, the serpentine WHS with natural gas as a backup (D) is the best alternative in 10 out of 13 cases, while the natural gas WHS (A) was the best alternative in 3 out of 13 cases. These results are consistent with those of Hang et al. [7]. Surprisingly, the electric water heater (B) moved from last position to second position when the natural gas WHS (A) or itself (B) was used as a reference. One advantage of taking the alternative with the highest impact as a reference is that all the impacts calculated are between 0 and 1. When taking an alternative as a reference (Equation (2)), the impact of the other alternatives is not bounded, and if the alternative taken as a reference has a very low impact in any of the subcriteria in comparison to other alternatives, the calculated relative impact of the other alternatives can be very high according to Equation (3). By way of illustration, the impact of a heat pipe with natural gas as a backup (F) on floor space when taking electricity alone (B) as a reference is 58.655 and its overall impact, 6.641.

5. Conclusions

Domestic solar WHS have recognised potential to significantly reduce domestic energy consumption and GHG emissions for water heating. However, there are few comparative studies of types of solar flat plates, evacuated tubes and conventional WHS from a sustainable multi-criteria perspective that integrates environmental, social and economic aspects. The two research objectives stated in Section 1 were established to fill this knowledge gap. Consequently, the key technical contributions of the research are:

(1) It provides a multi-criteria decision-making tool that enables quantification of the sustainability of renewable and conventional domestic WHS by means of an Impact Index applicable to any location and demand. The MAUT, together with the Delphi method, proved effective in the creation of the tool. The application of the Delphi method to conduct surveys with which to identify impacts, define indicators and assign weights provides rigour and objectivity to the process of definition of the tool and to the tool itself. The tool considers the following aspects of economic, environmental and social sustainability: annual cost, material consumption, energy consumption, GHG emissions, space requirement, visual impact and occupational risks. The tool could help energy policy makers, installers and users of domestic WHS when they are deciding on the best WHS from a sustainability perspective. The proposed set of weights assigned by the experts can be used as an initial reference and adjusted.

(2) The tool has been applied to evaluate the 12 solar and conventional WHS indicated in Fig. 3 in a sport centre located in Barcelona, considering current applicable legislation. The dynamic thermal simulation programme T*SOL was used to dimension the solar thermal systems. From the application of the proposed tool, the following conclusions can be drawn:

a. While solar WHS perform better in terms of energy consumption and CO_2 emissions, they have a higher annual cost, material consumption and use more floor space than conventional WHS.
b. According to the Impact Index, natural gas WHS is the overall best system, very closely followed by the serpentine and harp flat plates, with natural gas as a backup WHS, according to the current preferences assigned by the experts, which resulted in the economic impact accounting for half of the total importance in the case study.
c. The sensitivity analyses of the weights provide deeper insight into the subject. In the first sensitivity analysis, with slight changes in the weights aimed at increasing

the importance of cutting energy consumption and CO_2 emissions, the serpentine flat plate WHS with natural gas as a backup is the best option.

d. The second sensitivity analysis focused on changes in the result when the reference used to calculate the impact was changed. The results provide more evidence that some types of solar WHS are preferable to conventional systems, since the serpentine flat plate WHS with natural gas as a backup ranked as the best alternative in 10 out of 13 cases.
e. Another interesting finding is that flat plate collectors rank better than evacuated tube collectors for all the weight sets considered in the two sensitivity analyses when compared within the same backup system (either natural gas or electric water heater) for the studied location and demand.
f. A natural gas-fired condensing boiler is preferred to an electric water heater as a backup system or as a conventional WHS.

To sum up, the results of the sensitivity analyses suggest that flat plate WHS with natural gas as a backup are the most sustainable alternatives of the twelve studied for Barcelona-like climate conditions and sport centre demand. Flat plate collectors are preferred to evacuated tube collectors and a natural gas-fired condensing boiler is preferred to an electric water heater as a backup system or as a conventional WHS.

The approach presented in the paper is interdisciplinary, covering several fields of knowledge: it connects engineering with economy, environment and society, that is, it looks at engineering from the perspective of sustainability. The approach uses an existing theory, the multi-attribute utility theory, and applies it to a new field: conventional and solar WHS. It has proved very useful at assessing these systems and can also be helpful in decision-making processes to select the most sustainable WHS for other locations and domestic hot water demands.

According to the present study and under the climatic and hot water demand conditions that were studied, policies incentivising flat plate solar WHS are justified, and even more so in a society that increasingly values the environment and requires cuts in GHG emissions and conventional energy consumption.

However, as the Impact Indexes are very similar between the alternatives, the results are highly dependent on society's priorities. Consequently, more research is needed on the establishment of widely accepted priorities between the different pillars of sustainability (the weight assigned to the criteria). Further applications of the proposed tool need to be carried out in locations with other climatic conditions to geographically expand knowledge, and with other hot water demands. The research could also be extended to other WHS such as a biomass condensing boiler or heat pump that could, presumably, be more sustainable than a natural gas-fired condensing boiler and an electric water heater.

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