Whole life design and resource reuse of an integrated collector-storage solar water heater

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Text revised on 06/04/18

Word count: 5918

Number of figures: 7

Number of tables: 4

Abstract

Passive solar systems are often designed primarily with efficiency in mind. This means that research efforts are concentrated towards gaining an increase in performance. However, due to the multiple materials used, their manufacturing processes, a lifespan that is usually shorter than that of a building a system is applied to, and the waste generated when it has reached the end of its useful life, a more holistic approach to the design and performance of these systems should be adopted.

This paper reports on the environmental impact of a unique integrated collector-storage solar water heater (ICSSWH) design, experimentally tested under Scottish weather conditions, considering circular economy and reuse potential. As such, the material flows and components used are mapped against the life-cycle stages of existing European standards, whilst ensuring an optimal efficiency. End of life considerations and design for disassembly and reuse are also assessed and discussed. The results show that a holistic design, which promotes circular economy principles, does not compromise efficiency and economic viability. Energy payback times of 4.5 and 4.6 years can be realised for a circular and linear approach, respectively. The biggest improvement comes from the operational carbon savings, which far outstrip the embodied carbon, with carbon payback times of just 7 months, when replacing an electric system.

Keywords: *Sustainability; Renewable energy; Recycling and reuse of materials; Energy*

1. Introduction

The consumption of heat accounts for 53% of the energy consumed by Scotland's homes and businesses, 13% of which is used for water heating, the second most significant energy use in homes (Wheelhouse, 2017). There are different types of solar water heating (SWH) systems that could contribute towards this demand. One such system is an integrated collector-storage solar water heater (ICSSWH) which is passive and direct, unlike many commercially available systems which are active and indirect. Active and indirect systems require a pump to circulate a heat transfer fluid, such as a glycol mixture, between an internal hot water storage tank and the collector. Passive and direct systems rely on natural convection to circulate potable water throughout the system.

Passive systems are vital to reduce energy demand in the built environment and for future energy sustainability. To truly evaluate the sustainability of such systems, it is important to compare the operational energy savings against the embodied energy. Scottish weather is not as forgiving as in a Mediterranean climate, therefore, the energy benefits of a SWH system are likely to be lower than in other, more climatically blessed, parts of the world, albeit the need for heat is greater. Therefore, the life-cycle is important to be able to make any claim about the overall benefits of a system; operational energy must offset embodied energy for it to be considered sustainable and to actively contribute to Scotland's climate targets (Scottish Government, 2017). Within a life-cycle perspective, the end of life stages are becoming more important due to resource scarcity. It is therefore imperative to consider reuse and recycling, thus keeping resources in the loop for as long as possible. This paper presents the first study of its kind in the UK, evaluating a unique ICSSWH system under Scottish weather conditions, designed with the circular economy and reuse potential in mind and aims to quantify its environmental impacts, in terms of energy and carbon.

2. Background

The system under investigation is a newly developed ICSSWH, the benefits of which are two-fold. Firstly, in terms of operational energy, it was designed to have a greater thermal performance than previous iterations due to an improvement in the design factors (discussed in Section 2.1). Secondly, in terms of life-cycle impacts and circular economy potential, it has been designed with disassembly in mind in order to keep resources in the loop for as long as possible and avoid, at the end of its useful life, all the materials in the system being processed as waste.

2.1 The ICSSWH system

There are many commercially available SWH systems and a major drawback is that they are active and indirect as opposed to passive and direct. Their distributed layout requires external hot water storage tanks and additional pipework, pumps, and valves. This yields a large space requirement and more complicated manufacture and installation processes (Arnaoutakis, Souliotis and Papaefthimiou, 2017). The more parts in the system and the more dispersed they are, the greater potential for heat loss and failure points; which reduces the efficiency and confidence in the system overall as well as increasing its environmental impact. This caveat calls for a condensed, all-in-one system that can be easily integrated into the roof structure, such as ICSSWH systems. These systems are passive and direct and as such do not require any additional components, such as pumps and control systems which depend on electricity, and therefore have lower economic and environmental costs (Wang *et al.*, 2015). The most common, commercially available systems are evacuated tube and flat plate collectors which, like ICSSWH systems, are cost effective and are able to pay back their investment within their service life (discussed in Section 2.2). The Energy Saving Trust (2011) conducted a study of 88 UK sites and found that these systems could provide as much as 60% of homes' hot water.

This translated to a cost saving from £30-£100 and a carbon saving from 50-500 kgCO2/year, depending on the heating system being replaced. While there are several types of SWHs (Jamar *et al.*, 2016), this paper focuses on a newly developed integrated collector-storage (ICS) system. As such it beyond the scope of this work to compare it with other technologies in terms of performance and cost.

The ICSSWH presented in this paper is an improved version of a prototype that has been previously modelled and validated (Garnier, Muneer and Currie, 2011; Birley *et al.*, 2012). It improves upon its predecessor through differing design configurations aimed at enhancing thermal performance and reducing operational energy by mitigating the use of conventional energy. Also, its innovative new design allows the system to be disassembled, thus improving its recycling potential. These configurations were chosen based on an extensive literature review surrounding ICS systems and Table 1 shows the design factors chosen for the collector under investigation. To this end, the system is being compared against itself, under different design conditions, as opposed to commercially available solar systems. However, for comparison, the functional units (FUs) of the ICSSWH against commercially available SWHs are illustrated in Figure 1. Here, the FU is defined as one SWH unit designed to provide domestic hot water for a single-occupancy dwelling, based on a consumption of 52 l/day, over a service life of 20 years.

With circular economy in mind, the system has been designed to allow the absorber plate to be detached from the storage tank. The absorber plate was made of aluminium for its high thermal conductivity despite its higher environmental impact, versus other common materials such as copper or stainless steel. The storage tank was made of stainless steel, with the two being sealed together using a rubber gasket. This greatly improves the collectors recycling potential as the steel and aluminium can be cleanly separated and reused. This design aspect was chosen to equip the system with a cradle-to-cradle, circular, potential.

Table 1: Summary of chosen design factors based on thermal performance.

Influence / ***Design factors***	*Thermal stratification (T_s) & Bulk water temperature (T_w)*	*Heat retention*	*Efficiency (η)*
Baffle plates *(Smyth et al., 2003; Kumar and Rosen, 2011; Swiatek et al,, 2015)*	Narrower gap between baffle & absorber and a shorter plate (~60% of the absorber length) produces greater T_s.	Heat loss can be reduced by 20% by perforating the plate.	η increases of up to 7% with the addition of a baffle (alongside additional insulation) and overall collection η of ~60%.
Heat transfer fins *(Junaidi, 2007; Garnier, 2009)*	Heat transfer increased 28% using aluminium fins; 18% with stainless steel (SS) - compared to an un-finned SS tank.	The high heat flux through the fins generates higher velocity flows, promoting heat loss during collection periods.	η improvement of 5-6% due to faster/greater heat transfer. Overall η using Al, 71%; SS, 65%.
Insulation/ Night cover *(Smyth et al.,, 2003; Kumar and Rosen, 2011)*	Optimising thickness & type of insulation (TIM honey-comb array showed best results) can give T_w between 40-50°C.	Insulating the vessels' top third, 60% of heat retained over the total volume. Temps were 2.8°C higher using an insulated night cover vs absorber coating.	1/3 insulated design showed 37% increase in heat retention & 13% higher collection η. Single glazing + night cover has η between 57.1-79.4%.
Inlet variations *(Hegazy, 2007; Farmahini-Farahani, 2012)*	Slotted & perforated pipes are effective at reducing mixing & improving T_s. Inlet position directly impacts T_s & the pipe being at the base of the tank gives the best T_s.	Due to the improvement in T_s, hot water retention at the top of the system can be improved through other methods, e.g. additional insulation or night cover.	A higher degree of T_s increases system η (by as much as 10%) as the bottom water layers are at a lower temp with more potential for heat gain.

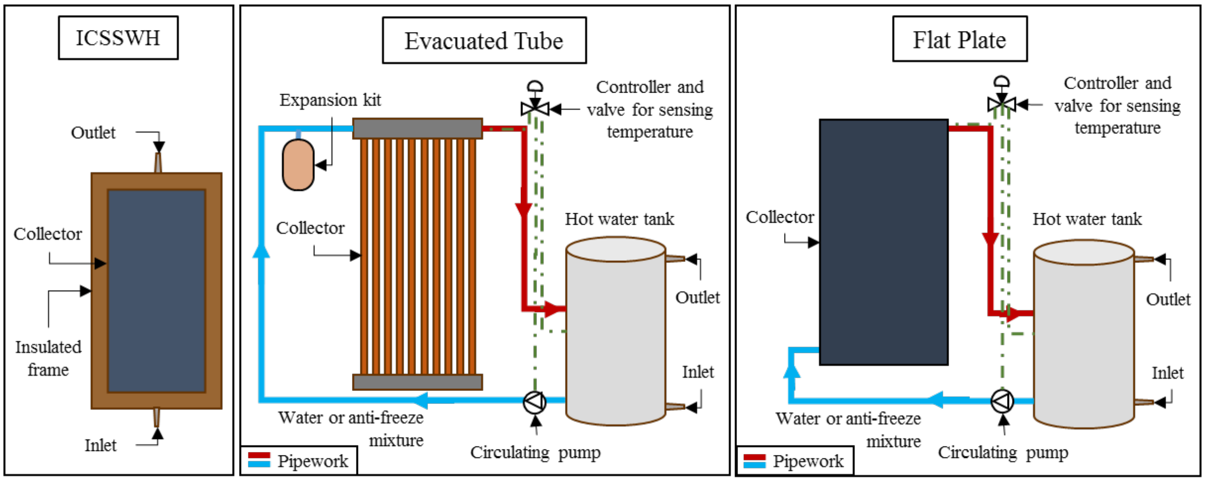

Figure 1: Diagrammatic view of ICSSWH, evacuated tube collector, and flat plate collector FUs.

Figures 2A and 2B illustrate the basic collector-storage unit and the insulated frame it sits in. Figure 2A shows the basic collector design while for the experimental testing two of these collectors are mounted side-by-side. Each collector has the same dimensions (1325 x 725 x 50mm), volume (48 l), absorber area (~1m^2), collector material, and insulated frame. The systems are under the same environmental conditions but with differing thermal efficiency design configurations as introduced in Table 1. One collector has three, 3mm thick, aluminium heat transfer fins welded vertically to the underside of the absorber plate. The other has a 4mm thick polycarbonate baffle plate that sits 5mm below the absorber plate creating a thin layer of water that can be ‘super-heated’ and then transferred, via buoyant convection, to the top of the water body. The aim of the fins is to increase heat transfer to the water body whilst the baffle plate should reduce heat loss by preventing reverse circulation at night. These systems, “Finned” and “Baffled” were tested against each other to create a thermal performance baseline.

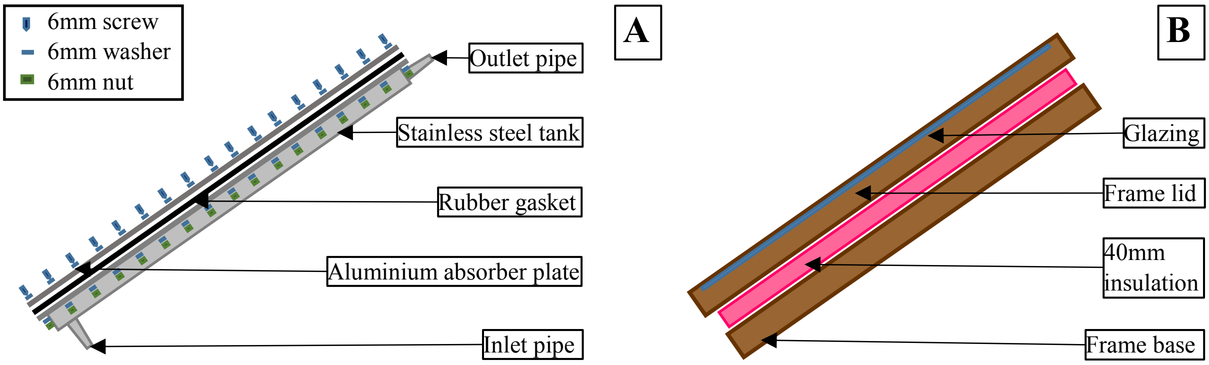

Figure 2: Schematic of [A] – the ICSSWH under investigation and [B] – the insulated frame the ICSSWH sits in.

As can be seen in Figure 2A, the ICS-SWH can be completely dismantled. This allows all its individual components to be recovered thus appealing to a circular economy. The environmental impact of this basic design and its subsequent heat retention additions will be analysed in the following sections.

2.2 Life cycle assessment of solar water heaters

There are a number of studies focussed on the life cycle assessment (LCA) of SWH systems. Most of these studies use electric or gas boilers as a basis for comparison and focus on commercially available systems (Greening and Azapagic, 2014). Uctug and Azapagic (2018) conducted a cradle-to-grave LCA for a passive, flat plate thermosiphon SWH in Turkey. The authors considered two scenarios; a linear LCA approach where the system components were processed as waste and a circular approach where they were recycled at the end of the service life. The construction stage proved to be the most energy intensive and had the biggest environmental impact and of the components, the water storage tank had the highest overall impact. However, environmental impacts are still 1.5–2 times lower when compared to gas boilers and the SWH could provide 80% of the annual hot water requirement. Kylili *et al.* (2018) carried out an environmental assessment of SWHs for industrial use in various European countries and found that 85% of the total environmental impact stems from the production and construction phases. They also found that SWHs could avoid over 70% of energy and carbon used/emitted when utilising conventional thermal systems. Similar energy results and environmental savings are found in other studies across the world with different types of SWH systems (Moore *et al.*, 2017; Balaji, Iniyan and Swami, 2018; Fertahi *et al.*, 2018). Further studies focus on the economic aspects of SWHs, showing their potential to replace conventional systems as well as justifying the need for government incentives (Araya *et al.*, 2017; Chen, Zhang and Dai, 2018; Rout, Sahoo and Thomas, 2018). However, these studies concentrate on hybrid systems (i.e. incorporating photovoltaics) or indirect, active systems.

Of the studies reviewed, only five have been conducted in the UK (Smyth, Eames and Norton, 2000; Allen *et al.*, 2010; Menzies and Roderick, 2010; Greening and Azapagic, 2014; Piroozfar, Pomponi and Farr, 2016) and only one on ICSSWH (Smyth, Eames and Norton, 2000). As a result of the increasing concern over our use of finite resources, the circular economy has emerged as a new paradigm which promises to decouple resource consumption from economic growth. A key element of the circular economy is to keep resources in the loop for as long as possible, thus maximising the re-usability of products, elements, and components. Whilst the concept is gaining momentum in many sectors, its uptake in the construction industry is lagging behind (Pomponi and Moncaster, 2017). For this reason, a cradle-to-cradle perspective has strongly characterised the improved design of the present system. An LCA will enable the quantification of the environmental benefits that may occur as a result of this design adaptation.

2.3 Life cycle assessment as a tool

LCA is an environmental management tool that allows the environmental impact of a product to be quantified. The different stages specific to buildings and construction products are shown in Figure 3, as stated in the British Standard EN 15978 (2011). The final supplementary Stage **D** allows a cyclic, holistic view of the full impacts of a product. It closes the loop and transforms an LCA from a linear analysis to circular, from cradle-to-grave to cradle-to-cradle. Cradle-to-cradle can have a very positive influence on LCA results as both reuse and recycling greatly reduce the environmental impact (Allen *et al.*, 2010).

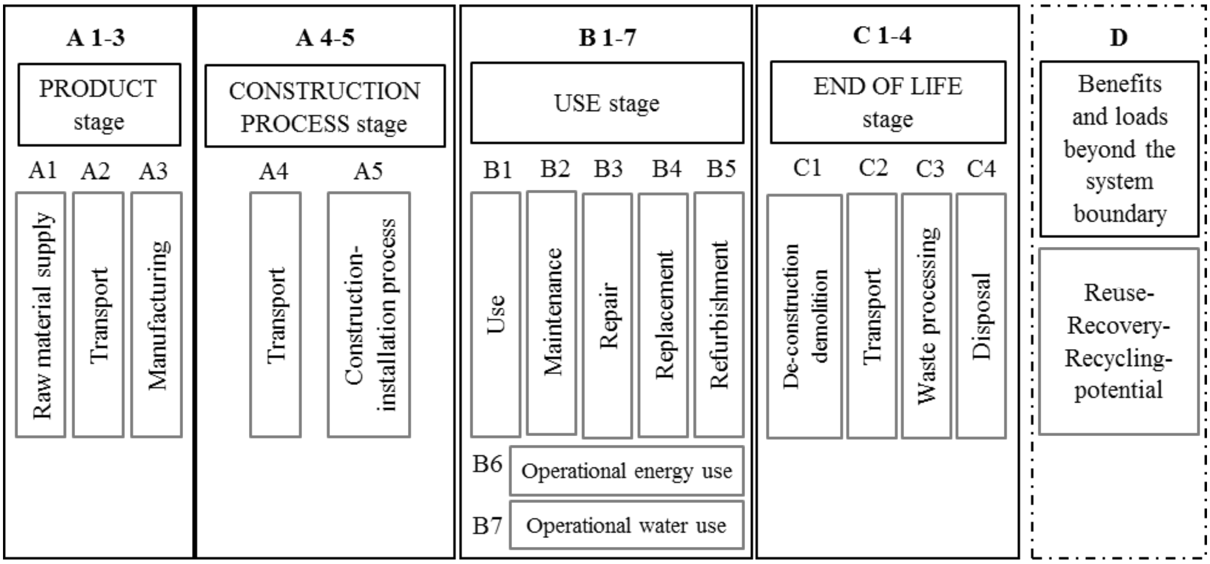

Figure 3: Different stages of the building life cycle (stages A-C) and supplementary information beyond (D). Adapted from (BSI, 2011).

Along with this environmental impact assessment, many of the studies reviewed in this paper also evaluate the energy and economic impacts. Combing these three aspects allows a detailed view of a products overall impact. Energy refers to the performance of the system and how much operational energy it can save over its useful life; this can pay back the system's embodied energy. Economy is heavily influenced by this as a higher system performance will reward more savings to the end-user in terms of avoided conventional energy consumption. Environment also relies on the system performance as the payback time for the embodied carbon depends on the carbon saved through the reduction of fossil fuel use. By utilising a solar, passive system, a proportion of conventional fossil fuels are replaced. The embodied energy can usually be recouped in under 2 years (Table 2). The economic payback periods (PBP) are reported to be much longer due to the higher capital costs of solar thermal systems compared to gas or electric boilers, for example. A life cycle cost analysis is beyond the scope of this paper, however, PBP reported in the literature are shown to give an idea of the potential of such systems. Table 2 summarises the cases presented in the literature, reviewing the country of each study (geographic location playing a large role in system performance); payback times (where reported); the life-span considered in each study; the stages of LCA covered (i.e. system boundaries) and; the methodology employed. Only European studies have been presented here as the databases and software used are more relevant to the current study.

The same methodology is rarely used throughout the literature, and this is not new in LCAs in the built environment (Pomponi and Moncaster, 2016). Many consider the ISO 14040 (2006) standard as the procedure to follow but use different databases and analytical software. The accuracy of the LCA relies on the integrity and applicability of the database used. There are numerous available however it is important to choose one that is most representative of the source and type of construction material used. Databases are often specific to geographic regions; for example, European databases include Ecoinvent, GaBi, and European Life Cycle Database whilst American databases include Athena and U.S. Life Cycle Inventory. Martínez-Rocamora, Solís-Guzmán and Marrero (2016) reviewed LCA databases focused on construction materials and presented a clear, informed selection process for researchers. The authors emphasised the high quality of Ecoinvent and GaBi Database for European studies. Software tools are used to minimise the time and effort required for a life cycle impact assessment (LCIA) and common tools include CML 2001, Eco-indicator 99, and Impact2002. Martínez *et al.* (2015) evaluated 7 software tools through a case study involving a wind turbine. The authors found that, although LCIA results across the different tools could vary markedly, CML and Eco-indicator 99 tools provided a robust and accurate comparison for most categories. The choice of database as well as the software tool is therefore a crucial consideration.

The spread in databases and software used makes direct comparison, as well as replicability, difficult. This inconsistency across the literature makes it hard to identify the steps within the LCA that have the greatest impact and, therefore, the greatest improvement potential (Ardente *et al.*, 2005). The majority of studies also claim to conduct a cradle-to-grave LCA which translates to stages **A** to **C** in the EN 15978 standard. However, results are often presented as aggregated indexes, i.e. each of the above factors is a bulk calculation, not taking into account the truncation error inherent in many material databases (Lenzen and Dey, 2000). Each tiny component included in the final functional unit (FU) has its own life-cycle and impacts though this is rarely considered, with the analysis only extending a short way into the components supply chain. Therefore, the more disaggregated the results, the more transparent and comprehensive the LCA.

2.4 Life cycle assessment methods: advantages and limitations

Three main methods for LCAs exist in the built environment: process, input-output, and the hybrid analysis. A process-based analysis refers to a mix of processes, products, and location-specific data to calculate and establish the environmental impact of a product system. Input-output analysis is an economic technique, which uses input-output tables (matrices of sector-based monetary transactions) to map resource consumption and pollutants release throughout the whole economy (Crawford, 2011). Both process and input-output LCAs suffer from incomplete and unreliable inventory data sources which impacts upon hybrid LCA, albeit with less severity (Crawford, 2008). Process LCA has inherent truncation errors due to the definition of system boundaries and the limited process data available (Lenzen, 2001). Input-output LCA has issues associated with data aggregation, however, if done correctly, the impact of this is typically much less than the truncation error in process LCA (Crawford and Stephan, 2013). Input-output LCA also suffers a downstream truncation error (Majeau-Bettez, Strømman and Hertwich, 2011) as it does not consider the 'gate-to-grave' period of the life cycle, however, this is easily overcome using input-output-based multipliers (Lenzen, 2001).

Hybrid analysis aims to combine the strengths of the previous two by filling missing, process-related information with input-output data, and it has been demonstrated that it is likely to yield more accurate results (Pomponi and Lenzen, 2018). However, combining process and input-output data in a hybrid LCA remains a highly manual and time-consuming process (Crawford *et al.*, 2017). Therefore, in the LCA of buildings - where each of the materials used has its own specific life-cycle and all interact dynamically in both space and time (Erlandsson and Borg, 2003; Collinge *et al.*, 2013) – the process-based analysis appears as the most reasonable choice and is also suggested by European and International Standards that are specifically developed for the construction sector (Moncaster and Song, 2012).

Table 2: Summary of literature surrounding LCA and SWHs in terms of payback times and methodologies.

		Payback Times (years)								
		Energy		**Environment**		**Economy**				
Paper	**Country of study**	Best	Worst	Best	Worst	Best	Worst	**Life-span (years)**	**LCA Stages**	**Method used**
Smyth, Eames and Norton (2000)	*UK*	>2							A 1-3	TRANSYS simulation & correlation program (Polysun 2000)
Tsilingiridis, Martinopoulos and Kyriakis (2004)	*Greece*			50%*	38%*			15	A-C	GaBi software; CML 2001
Ardente *et al.* (2005)	*Italy*	>2		>2	2			15	A-C	ISO 14040
Battisti and Corrado (2005)	*Italy*	0.42	1.3	0.42	1.6			15-20	A-C	Eco-it software; Eco-indicator 99
Tripanagnostopoulos *et al.* (2005)	*Italy*	1.3	1.6	1.2	2	14.2	22.1	15-25	A-D	SimaPro 5.1 software; CML 2 baseline 2000; Eco-indicator 95
Kalogirou (2009)	*Cyprus*	1.1		0.6	3.2	2.7	4.5	20	A 1-3	TRANSYS simulation & correlation program (Polysun 2000)
Allen *et al.* (2010)	*UK*	1.3	5.2	1.2	2	15	85	25	A 1-5	SimaPro v.7.1 software; data directly from manufacturers
Menzies and Roderick (2010)	*UK*	2.6	6.1	3.5	8.2			20	A-C	University of Bath Inventory of Carbon and Energy v.1.6a
Laborderie *et al.* (2011)	*France*	>1	1.5	0.42	0.5			20-25	A-D	Impact 2002+ (v2.04); SimaPro 7.1; Eco-invent 2.0 database
Koroneos and Nanaki (2012)	*Greece*					4	6	20	A-C	ISO 14040; GEMIS software; Eco-indicator 99 & Eco-indicator 95
Carnevale, Lombardi and Zanchi (2014)	*Italy*	0.7	1.2	0.65	1.1			25	A-D	ISO 14040; Eco-invent 2.2; Eco-indicator 95
Comodi *et al.* (2014)	*Italy*	0.2	1	0.1	2.5	3	13	10	A-C	Tolomeo software; GaBi database; Eco-indicator 99 (E199-EE)
Greening and Azapagic (2014)	*UK*	93%*	82%*	94%*	87%*			25	A-C	ISO 14040 & 14044; GaBi software v.4.4 & CML 2001
Chen *et al.* (2015)	*Ukraine*	3.8	8.3	1.9	7.2			10-15	A-C	SimaPro v.7.0; Eco-indicator 95
Lamnatou *et al.* (2015)	*France/ Spain*	0.5	2					30	A-C	Impact 2002+; Eco-indicator 99
Uddin and Kumar (2016)	*Thailand*	0.2	0.6					15	A-C	SimaPro 7.3.3 database; Eco-indicator 99 and CML 2000
Zambrana-Vasquez *et al.* (2015)	*Spain*	0.6	4.35	72%*	30%*			20	A-C	CHEQ4 v.1.3 software; METASOL
Piroozfar, Pomponi and Farr (2016)	*UK*	62%*		<6				20	A-C	SimaPro 8.0.3.14 ; Eco-invent (2013) database
Arnaoutakis, Souliotis and Papaefthimiou (2017)	*Greece*			96%*				10	A-C	SimaPro 8.2; Eco-invent v.3.3; Eco-indicator 99
Kylili *et al.* (2018)	*Greece*	75%	71%	74%	68%			20	A-B	ISO 14040; GaBi software

* *Did not calculate payback time in years but expressed as % avoided compared to conventional systems, **if stated at all**. [Arnaoutakis et al. (2017) compared against a Flat Plate unit]*

Stated payback times depend heavily on the systems reviewed, the conventional systems they're compared to and the energy mix and climate of the geographical location. Large spread of systems/configurations/comparisons throughout the literature.

Given that a number of studies utilise the ISO 14040 (2006) methodology, that framework will also be adhered to in this work. An LCA consists of four main steps – goal and scope definition (investigation boundaries); life cycle inventory (LCI); life cycle impact assessment (LCIA); interpretation of results/improvement analysis. This paper covers a cradle-to-cradle LCA; the materials of the newly developed ICSSWH, designed with attributes considering their reuse and recycle potential, are presented in Section 3.

3. Methodology

3.1 Goal and Scope

The goal of the present research is to determine the environmental impact of a newly developed ICSSWH under three different design configurations, as discussed in Section 2.1. By determining the embodied energy and operational energy savings throughout the systems life-time, its sustainability can be quantified. Also, reviewing the embodied energy both with and without a circular economy approach, allows to quantitatively evaluate the importance of a 'circular' design. A process-based LCA will be undertaken for this work.

The FU is defined as one ICSSWH designed to provide hot water for one person, 52 l/day. One FU includes the collector and the insulated frame, detailed in Figures 2A and 2B. Pipework to and from the collector storage tank is excluded as it is assumed that, as with other traditional systems, this is already in place before the installation of the unit. The system boundaries are considered to be where the FU interfaces with the rest of the domestic hot water system. Figure 4 illustrates the boundaries of the cradle-to-cradle LCA undertaken in the present paper.

Given that each ICSSWH collector has a different initial set-up, "Finned" vs "Baffled", the cradle-to-gate stage will play a key role due to the use of different materials. In terms of the service life of the system, based on the literature review, a lifespan of 20 years is assumed.

Transport within each relevant stage was taken to be 50km as it is assumed that any necessary travel, such as from manufacturer to site or site to landfill, is within a 50km radius.

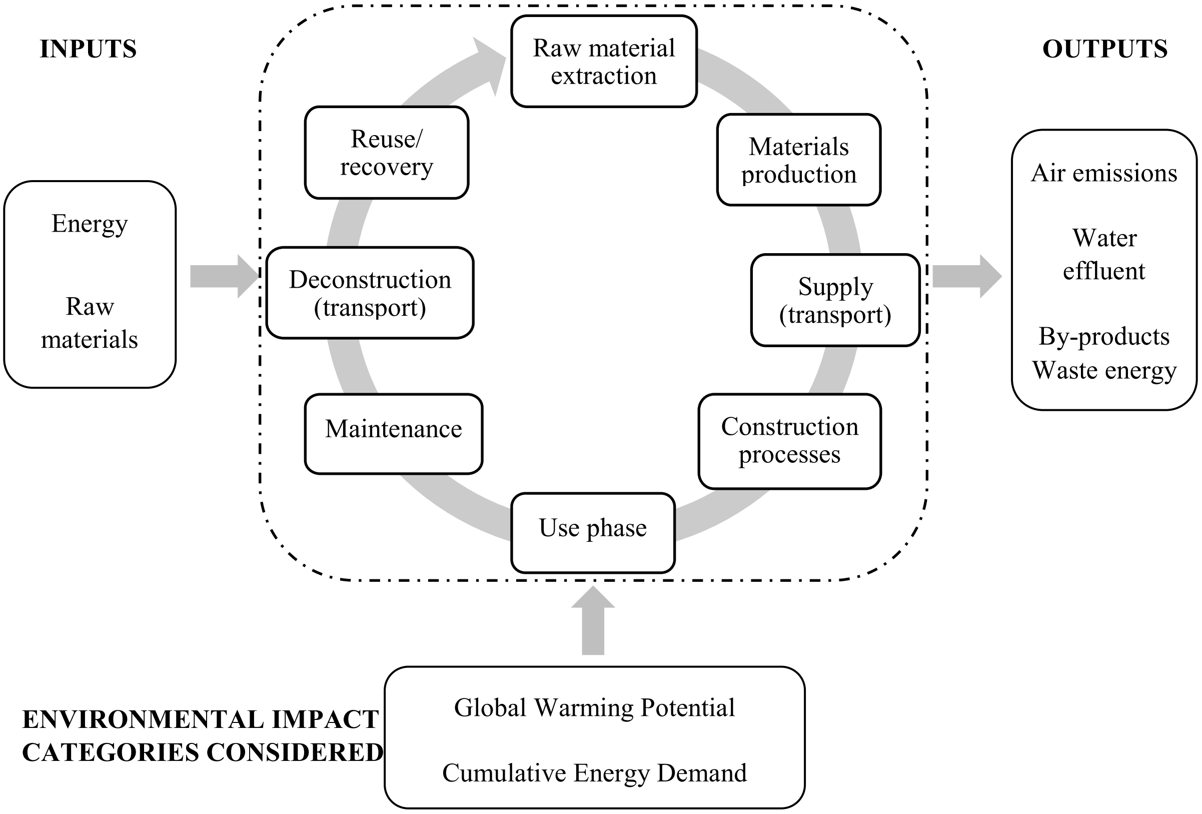

Figure 4: LCIA based on (BSI, 2011). Dashed line indicates assessment boundary. Embodied carbon is defined here as GWP 100 based on IPCC (2013).

3.2 Life cycle inventory (LCI)

Tables 3 and 4 outline the primary data collected for the materials used in the construction of the FU, plus the additional materials for the different design configurations. The percentage of the overall mass for each component has been calculated and from this the materials that can be neglected are determined. The ISO 14040 (2006) standard states that if the effect of a system component is less than 1% on the overall mass it can be neglected from the analysis. However, to keep the LCA as transparent as possible a cut-off criteria of 0.5% on the mass has been applied in this analysis.

3.3 Life cycle impact assessment (LCIA)

The LCIA can be broken down into two main contributors – operational energy and embodied energy – which combine to give the total energy impact of a system. As stated in the goal and scope, the embodied energy analysis will be from both cradle-to-grave (without circular economy) and cradle-to-cradle (with circular economy). The embodied energy is derived from the energy expended during the manufacture, transport, installation, maintenance and deconstruction of the FU which is added to give a positive impact on the total energy. The operational energy is derived from the "use" stage of the FU's life-cycle; in this research it is considered as the amount of conventional energy avoided and therefore contributes a negative impact on the total energy.

The LCA tool used in this research is OpenLCA v1.6.2 equipped with the Ecoinvent database v3.1 and global data was selected. The impact assessment method used for the embodied carbon (GWP 100) is the CML Baseline (v4.4, January 2015) and the Cumulative Energy Demand (CED, v1.0.1, January 2015) for embodied energy. These tools were adopted based on the types of databases and analytical software commonly used, reviewed in Section 2.3.

In terms of the operational energy, the energy savings related to hot water use will be quantified based on validated fieldwork data. Given that a full annual test is still undergoing for the newly developed ICSSWH in this study validated data from previous experiments will be used as a conservative hypothesis. The new system has been designed to be more efficient and initial results have identified additional savings, however, a full year of tests has yet to be concluded in order to provide comparable data. Therefore, as a conservative approach the energy savings from a successfully completed test, validated with field data, of a previous prototype of the system will be used (Garnier, Muneer and Currie, 2011).

Table 3: Primary data of employed materials and their masses for the FINNED collector.

Collector

Component	Material	Quantity	Mass (total), kg	% Overall Weight
Tank Base	Stainless Steel	1	14.4	20.9
Absorber Plate (with FINS)	Aluminium	1	9.7	14.1
Absorber Plate Coating	Black Spray Paint	4 coats	0.704	1.0
Sparge Tube	Copper	1	0.58	0.8
Gasket	EPDM rubber	1	0.37	0.5
Gasket Sealant	Hylomar	1	0.1	0.1
Compression Reducing Coupling	Copper	1	0.1	0.1
Compression Straight Coupling	Copper	1	0.07	0.1
Hose Fitting	Copper	1	0.014	0.02
Screws	Steel	44	1.012	1.5
Nylock Nuts	Stainless steel	44	0.132	0.2
Washers	Steel	88	0.2552	0.4
Sparge Tube Supports	Polycarbonate	2	0.0018	0.003

Frame

Component	Material	Quantity	Mass (total), kg	% Overall Weight
Glazing	Glass	1	11.0	16.0
Frame	Plywood	1	28.3	41.2
Screws	Steel	32	0.02	0.029
Sealant	Silicon	1	0.005	0.007
Insulation	PU insulation	1	2.0	2.9
Waterproofing	Black Paint	1	0.005	0.007
			68.8	**100.0**

Table 4: Primary data of employed materials and their masses for the BAFFLED collector.

Collector

Component	**Material**	**Quantity**	**Mass (total), kg**	**% Overall Weight**
Tank Base	Stainless Steel	1	14.4	20.8
Absorber Plate	Aluminium	1	8.5	12.3
Absorber Plate Coating	Black Spray Paint	4 coats	0.704	1.0
Sparge Tube	Copper	1	0.58	0.8
Gasket	EPDM rubber	1	0.37	0.5
Gasket Sealant	Hylomar	1	0.1	0.1
Compression Reducing Coupling	Copper	1	0.1	0.1
Compression Straight Coupling	Copper	1	0.07	0.1
Hose Fitting	Copper	1	0.014	0.02
Screws	Steel	44	1.012	1.5
Nylock Nuts	Stainless steel	44	0.132	0.2
Washers	Steel	88	0.2552	0.4
Sparge Tube Supports	Polycarbonate	2	0.0018	0.003
Baffle Plate	Polycarbonate	1	1.55	2.2
Baffle Plate Supports	Polycarbonate	3	0.0009	0.001

Frame

Component	**Material**	**Quantity**	**Mass (total), kg**	**% Overall Weight**
Glazing	Glass	1	11.0	15.9
Frame	Plywood	1	28.3	40.9
Screws	Steel	32	0.02	0.029
Sealant	Silicon	1	0.005	0.007
Insulation	PU insulation	1	2.0	2.9
Waterproofing	Black Paint	1	0.005	0.007
			69.1	**100.0**

3.4 Improvement analysis

This fourth stage in the LCA process, concerned with the interpretation and identification of the potential for impact reduction, is beyond the scope of this study. However, the ongoing work will look at the following possible contributions to reduce both the embodied carbon and embodied energy of the ICSSWH, though they will not be evaluated here. The embodied impacts could be improved or targeted in a number of ways: In terms of materials, the collector absorber plate could be made from 1.5mm aluminium as opposed to 3mm and the use of recycled materials in the product stage will reduce both the energy requirements and greenhouse gas emissions. However, this would need to be accompanied by a structural optimisation analysis to determine the effect, if any, on the efficiency and structural integrity of the collector which may have a knock-on effect on payback periods for both energy and carbon.

In terms of increasing operational carbon and energy savings, improving the efficiency of manufacturing processes, as well as the thermal efficiency of the ICSSWH itself, the savings will be more pronounced, thus reducing energy and carbon payback times. Optimising the operational efficiency of the system, in order to improve the operational energy savings, is a major part of the ongoing work and the design factors being assessed are shown in Table 1. These additional components will have an impact on the LCIA but the improvement in operational energy savings are anticipated to nullify this. Also, increasing the lifespan of the collector would reduce impacts due to the prolonged operational energy and carbon savings thus displacing fossil fuels for longer. Finally, by disaggregating the LCA and reviewing the impacts per life-cycle stage, as shown in Figure 3, the stages with the largest impacts can be identified and improvement efforts can focussed thus.

4. Results and Discussion

For the LCIA four scenarios were developed:

- Finned ICSSWH without stage D – ‘Finned Linear’
- Baffled ICSSWH without stage D – ‘Baffled Linear’
- Finned ICSSWH with stage D – ‘Finned Circular’
- Baffled ICSSWH with stage D – ‘Baffled Circular’

For each scenario, using global data in Ecoinvent v3.1, GWP 100 and Cumulative Energy Demand (CED) were determined by inputting the masses of each material detailed in Tables 3 and 4. The raw data for all eight cases are provided in the supplementary data. For components made of the same material the total quantity was summed and added to the process flow. When a product, or a reasonably similar product, could not be found in the database the Environmental Product Declaration (EPD) was searched. An EPD is a voluntary environmental impact statement for a product or system, allowing consumers to objectively compare the environmental performance of products. In the current analysis, only full life-cycle data for the tank frame insulation and stage D data for the polycarbonate baffle plate were not listed in the database. The full life-cycle EPD for the insulation (IVPU, 2015) was found and the values for GWP 100 and CED were added to the final LCIA output. Unfortunately, stage D data for the polycarbonate could not be found and was thus omitted from the analysis.

The data produced from the LCIA was evaluated by comparing the embodied impacts against the operational savings both with and without the circular economy aspect in mind. This was done to highlight the benefit of a circular economy approach as well as emphasise the fact that the presented ICSSWH system allows for this through its design for disassembly. The following results and corresponding discussion divides the LCIA into energy impacts and carbon impacts.

4.1 Energy impact

The energy impact is defined here as the embodied energy required throughout the FU's life-cycle, with and without a circular economy approach, and the operational energy savings gained from the collector. As stated previously, a reference collector is used and the potential operational energy savings, by hot water provided by the system and conventional energy avoided, are illustrated in Figure 5. It can be seen that there is considerable potential for an ICSSWH system to displace conventional energy thus offering significant operational energy savings.

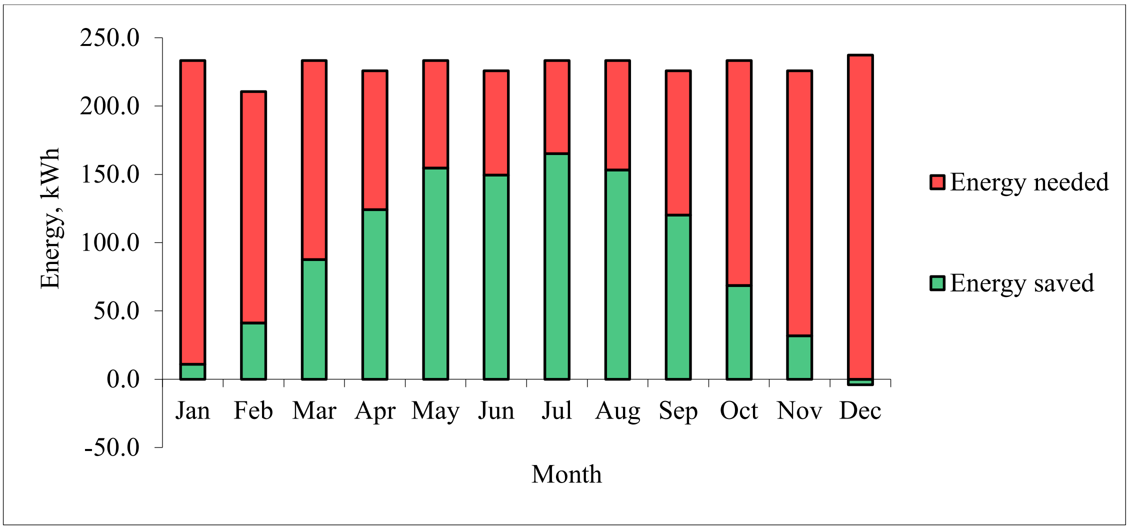

Figure 5: Total energy needed by the end user each month, over the course of a year, including the operational energy contribution from the reference collector (energy generated by the system).

Figure 6 shows the LCIA results for the embodied energy of the two base configurations, the finned and baffled collectors, from a linear (cradle-to-grave) and circular (cradle-to-cradle) approach. These values are graphed alongside the operational energy savings that the reference collector can provide. A logarithmic scale was used as the embodied impacts and operational savings differ by an order of magnitude. The log scale allows for an easier comparison.

Embodied energy is very similar for both the circular and linear scenarios. Although materials are reused in a circular economy (thus regaining some of the energy spent), energy must also be expended in the deconstruction process. In order to segregate waste, and to ensure that the different system components can be reused/recycled/recovered, some extra activities are needed aside from just transporting waste to a skip and onto landfill. The percentage improvement in embodied energy in a circular versus linear economy are 2.8% and 2.6% for the finned and baffled collectors, respectively.

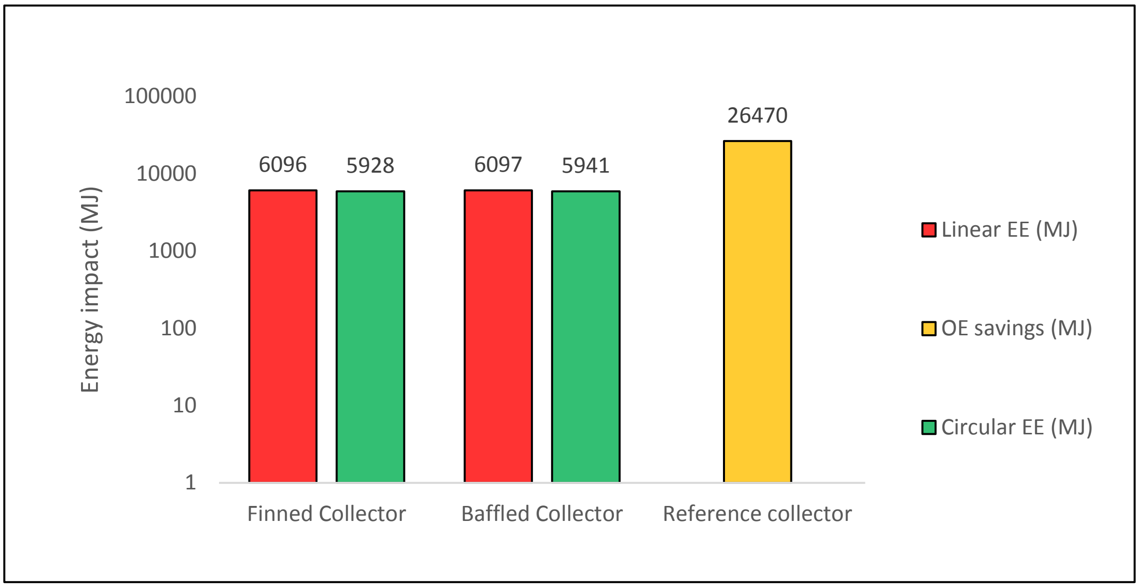

Figure 6: Embodied energy (EE) of the finned and baffled collectors, considering a linear and circular economy approach, alongside the operational energy (OE) savings from the reference collector. Note: a logarithmic scale is used.

Not only is there very little difference between the LCIA approaches but also between the collector designs with the finned system showing a very slight advantage over the baffled, most likely due to the greater impact of reusing aluminium. However, the stage D impact for the polycarbonate baffle plate could not be sourced, therefore, its percentage improvement will deviate slightly from the presented value. It is likely that its inclusion would only improve the GWP 100 results, however.

In terms of the operational energy savings, a payback an order of magnitude greater than the input is observed (Fig. 6). This demonstrates that the reference collector, a previous, less efficient prototype, is more than capable of recovering its embodied energy within its lifetime. Energy payback times were found to range from 4.5 to 4.6 years, for a circular and linear approach, respectively. Even if the energy savings are insignificant when choosing a circular approach over linear, the carbon savings more than make up for this shortfall.

4.2 Carbon impact

The carbon impact is defined here as the embodied carbon (GWP 100) required throughout the FU's life-cycle, with and without a circular economy approach, and the conservative operational carbon savings afforded by the reference collector. Figure 7 shows the LCIA results for the embodied carbon of the two base configurations, again from a linear and circular approach. These values are graphed alongside the operational carbon savings from the reference collector, where both natural gas and electricity have been replaced. For this, the annual operational energy (in kWh) was converted to carbon dioxide equivalent (kgCO_{2e}) using conversion factors published by the Department for Business, Energy & Industrial Strategy (DBEIS, 2017) Again, a logarithmic scale was used as the embodied impacts and operational savings differ by an order of magnitude here.

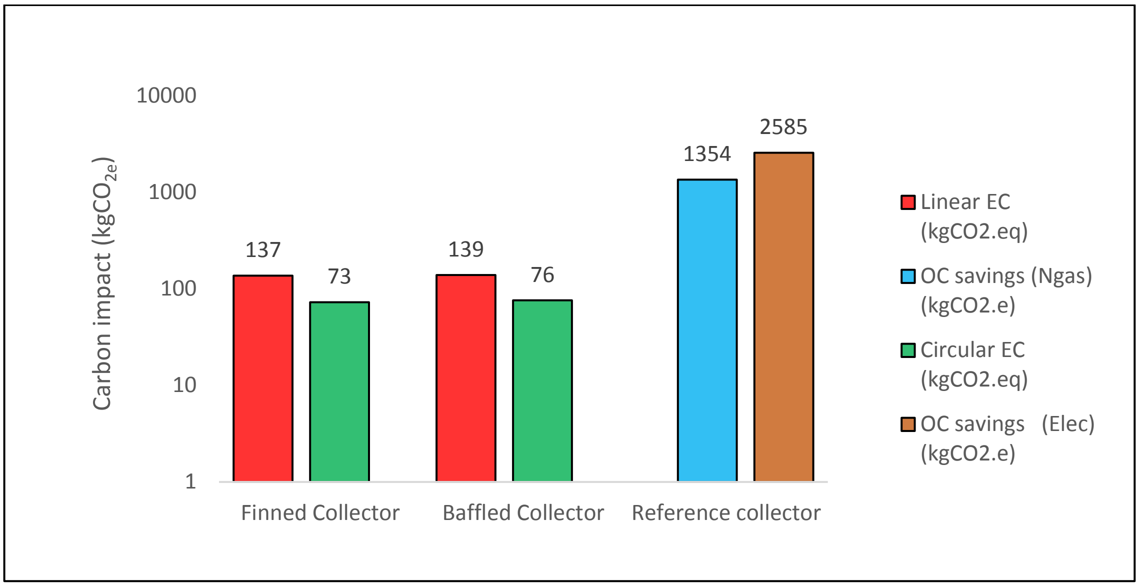

Figure 7: Embodied carbon (EC) of the finned and baffled collectors, considering a linear and circular economy approach, alongside the operational carbon (OC) savings from the reference collector, considering the replacement of natural gas (Ngas) and electricity (Elec). Note: a logarithmic scale is used.

A much more significant difference between the linear and circular approach is noticed here. The percentage improvement in embodied carbon in a circular versus linear economy is 47%

and 45% for the finned and baffled collectors, respectively. The carbon impact in a circular economy is almost half that in a scenario where stage D is not considered. This very clearly highlights the benefit of employing a circular approach as opposed to simple disposal at the end of the products useful life. Again, there is only a slight difference between the finned and baffled collectors in both scenarios with finned having a marginally better result. This is again most likely due to the reuse of the metal components though this margin may close with the addition of the stage D data for the polycarbonate baffle plate, omitted here as discussed earlier.

In terms of the operational carbon savings, a payback an order of magnitude greater than the input is observed for a circular economy approach (Fig. 7). This demonstrates that the reference collector can very quickly recover its embodied carbon. Carbon payback times, when compared to an electric system were found to range from 7 to 13 months, for a circular and linear approach, respectively. When replacing natural gas, payback times ranged from 13 to 25 months, for a circular and linear approach, respectively. This reflects the large difference between energy sources, electricity being far more carbon intensive than natural gas and reinforces the necessity to always consider embodied carbon along embodied energy as the latter is only able to provide partial information for it neglects the carbon intensity of the energy carrier. However, the current conversion factor for electricity is relatively low compared with recent years which shows the increased contribution of renewable energies into the UK national grid.

4.3 Assumptions

A number of assumptions were applied to the LCIA:

- The components made of the same material were aggregated assuming that they are all under the same inventory category

- Under the linear approach, without circular economy in mind, it is assumed that the entire ICSSWH is disposed of in a landfill at the end of its useful life
- In terms of transport, it was assumed that a 50km radius from the installation site was a generic representation for the manufacturer, the landfill, and waste processing facilities. Also, the most environmentally friendly transport option was selected as the end of life scenario will take place 20 years in the future and it is assumed that technology will improve.
- It is assumed that the conversion factors applied in this work for natural gas and electricity will not change over the lifespan of the collector.
- Thermal performance degradation over the collector's 20 year lifespan was not considered.

5. Conclusions

This paper aimed to present the first study of its kind in the UK; a unique ICSSWH design, experimentally tested under Scottish weather conditions, which considers circular economy and reuse potential in a life cycle perspective. Due to the high demand for heat in Scotland, alongside international efforts to mitigate climate change, an alternative to conventional fossil fuel driven energy systems is required. The novel ICSSWH presented in this paper is a potential alternative that aims to partially replace conventional energy sources with respect to the production and delivery of domestic hot water.

In order to evaluate the sustainability of the ICSSWH system, the embodied impacts and operational savings across its lifetime must be compared. The results of the LCA, employed to convey such a comparison, have been presented and discussed. The analysis was completed for four scenarios: for an ICSSWH incorporating fins and an ICSSWH with a baffle plate and each evaluated with and without a circular economy approach. The results showed that the embodied energy varied very little with a circular approach versus linear. Utilising a circular economy approach garnered an improvement of 2.8% and 2.6% for the finned and baffled systems, respectively. When compared against the operational energy savings, an energy payback an order of magnitude greater than the input is observed, with payback times of 4.5 and 4.6 years for a circular and linear approach, respectively. This shows that the system is easily capable of recovering its embodied energy throughout its lifetime.

The most significant difference between a circular and linear approach comes when evaluating the embodied carbon. An improvement in a circular versus linear economy of 47% and 45% is observed for the finned and baffled systems, respectively. This substantial decrease of embodied carbon highlights the importance and advantages of a circular economy approach. Using the operational carbon savings, which far outstrip the embodied carbon, carbon payback times of just 7 months can be realised, when replacing an electric system.

However, there are caveats. As an LCA is run over such a long time, 20 years taken here as the working lifetime of the ICSSWH, there is inherent uncertainty. Therefore, the resulting figures must be taken with a pinch of salt as there are several sources of uncertainty within the process. Also, further limitations of this study are related to the lack of sensitivity analysis for the LCA and the inherent truncation error in process LCA, as discussed in Section 2.2. Truncation errors can normally be as high as 70%. While this should be addressed in further work through a hybrid analysis, the difference between embodied carbon and operational carbon savings is so significant in this case that the system would still amply pay its embodied carbon back even if it were twice as much (i.e. a truncation error of 100%). The benefits of a circular economy approach within the built environment cannot be denied. The system presented here has been designed with this in mind, as each component can be separated and reused. This allows the materials to be recovered and put back in the loop, with great potential for material reuse, which is a marked improvement on landfill disposal.

Finally, when comparing the payback times presented here with values reported in the literature (Table 2) it is apparent that, in terms of embodied carbon and embodied energy, the newly designed ICSSWH is consistent with figures reported for the UK.

Future work will involve an improvement analysis aimed at optimising operational efficiency which will have a knock-on effect on energy and carbon payback times. Also, by disaggregating the LCA stages and conducting a sensitivity analysis, the areas where the greatest improvement could be focussed can be identified.

Figure captions

Table captions

References

Allen, S. R. *et al.* (2010) ‘Integrated appraisal of a Solar Hot Water system’, *Energy*. Elsevier Ltd, 35(3), pp. 1351–1362. doi: 10.1016/j.energy.2009.11.018.

Araya, R. *et al.* (2017) ‘Life-cycle savings for a flat-plate solar water collector plant in Chile’, *Renewable Energy*. Elsevier Ltd, 112, pp. 365–377. doi: 10.1016/j.renene.2017.05.036.

Ardente, F. *et al.* (2005) ‘Life cycle assessment of a solar thermal collector’, *Renewable Energy*, 30, pp. 1031–1054. doi: 10.1016/j.renene.2004.09.009.

Arnaoutakis, N., Souliotis, M. and Papaefthimiou, S. (2017) ‘Comparative experimental Life Cycle Assessment of two commercial solar thermal devices for domestic applications’, *Renewable Energy*. Elsevier Ltd, 111, pp. 187–200. doi: 10.1016/j.renene.2017.04.008.

Balaji, K., Iniyan, S. and Swami, M. V. (2018) ‘Exergy, economic and environmental analysis of forced circulation flat plate solar collector using heat transfer enhancer in riser tube’, *Journal of Cleaner Production*. Elsevier Ltd, 171, pp. 1118–1127. doi: 10.1016/j.jclepro.2017.10.093.

Battisti, R. and Corrado, A. (2005) ‘Environmental assessment of solar thermal collectors with integrated water storage’, *Journal of Cleaner Production*, 13, pp. 1295–1300. doi: 10.1016/j.jclepro.2005.05.007.

Birley, P. *et al.* (2012) ‘CFD Study of an Integrated Collector Storage Domestic Solar Hot Water System’, in *Eurosun 2012*. Rejika, Croatia.

BSI (2011) *BS EN 15978:2011 Standards Publication Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method*. London.

Carnevale, E., Lombardi, L. and Zanchi, L. (2014) ‘Life Cycle Assessment of solar energy systems : Comparison of photovoltaic and water thermal heater at domestic scale’, *Energy*. Elsevier Ltd, 77, pp. 434–446. doi: 10.1016/j.energy.2014.09.028.

Chen, G. *et al.* (2015) ‘Comparative field experimental investigations of different flat plate solar collectors', *Solar Energy*. Elsevier Ltd, 115, pp. 577–588. doi: 10.1016/j.solener.2015.03.021.

Chen, J. F., Zhang, L. and Dai, Y. J. (2018) 'Performance analysis and multi-objective optimization of a hybrid photovoltaic/thermal collector for domestic hot water application', *Energy*. Elsevier Ltd, 143, pp. 500–516. doi: 10.1016/j.energy.2017.10.143.

Collinge, W. O. *et al.* (2013) 'Dynamic life cycle assessment: Framework and application to an institutional building', *International Journal of Life Cycle Assessment*, 18(3), pp. 538–552. doi: 10.1007/s11367-012-0528-2.

Comodi, G. *et al.* (2014) 'LCA analysis of renewable domestic hot water systems with unglazed and glazed solar thermal panels', *Energy Procedia*. Elsevier B.V., 61, pp. 234–237. doi: 10.1016/j.egypro.2014.11.1096.

Crawford, R. H. (2008) 'Validation of a hybrid life-cycle inventory analysis method', *Journal of Environmental Management*, 88(3), pp. 496–506. doi: 10.1016/j.jenvman.2007.03.024.

Crawford, R. H. (2011) *Life cycle assessment in the built environment.* Taylor & Francis.

Crawford, R. H. *et al.* (2017) 'Towards an Automated Approach for Compiling Hybrid Life Cycle Inventories', *Procedia Engineering*. The Author(s), 180, pp. 157–166. doi: 10.1016/j.proeng.2017.04.175.

Crawford, R. H. and Stephan, A. (2013) 'The Significance of Embodied Energy in Certified Passive Houses', *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering*, 7(6), pp. 427–433.

DBEIS (2017) *Greenhouse gas reporting: conversion factors 2017*. Available at: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2017.

Energy Saving Trust (2011) 'Here comes the sun: a field trial of solar water heating systems'.

Erlandsson, M. and Borg, M. (2003) 'Generic LCA-methodology applicable for buildings, constructions and operation services - today practice and development needs', *Building and Environment*, 38(7), pp. 919–938. doi: 10.1016/S0360-1323(03)00031-3.

Farmahini-Farahani, M. (2012) 'Investigation of four geometrical parameters on thermal stratification of cold water tanks by exergy analysis', *International Journal of Exergy*, 10(3), pp. 332–345. doi: 10.1504/IJEX.2012.046814.

Fertahi, S. ed D. *et al.* (2018) 'Design and thermal performance optimization of a forced collective solar hot water production system in Morocco for energy saving in residential buildings', *Solar Energy*. Elsevier, 160(December 2017), pp. 260–274. doi: 10.1016/j.solener.2017.12.015.

Garnier, C. (2009) 'Performance measurement and mathematical modelling of integrated solar water heaters.', *PhD Thesis*.

Garnier, C., Muneer, T. and Currie, J. (2011) 'Thermal model for performance prediction of integrated collector storage systems', *Journal of Renewable and Sustainable Energy*, 3(1), pp. 0–17. doi: 10.1063/1.3549148.

Greening, B. and Azapagic, A. (2014) 'Domestic solar thermal water heating: A sustainable option for theUK?', *Renewable Energy*. Elsevier Ltd, 63, pp. 23–36. doi: 10.1016/j.renene.2013.07.048.

Hegazy, A. A. (2007) 'Effect of inlet design on the performance of storage-type domestic electrical water heaters', *Applied Energy*, 84(12), pp. 1338–1355. doi: 10.1016/j.apenergy.2006.09.014.

IPCC (2013) *Climate Change 2013*.

ISO14040 (2006) 'Environmental management — Life cycle assessment — Principles and framework'. Geneva, Switzerland.

IVPU (2015) *Environmental Product Declaration*. Available at: www.bau-umwelt.com / https://epd-online.com.

Jamar, A. *et al.* (2016) ‘A review of water heating system for solar energy applications’, *International Communications in Heat and Mass Transfer*. Elsevier Ltd, 76, pp. 178–187. doi: 10.1016/j.icheatmasstransfer.2016.05.028.

Junaidi, H. A. (2007) ‘Optimized Solar Water Heater for Scottish Weather Conditions’.

Kalogirou, S. (2009) ‘Thermal performance , economic and environmental life cycle analysis of thermosiphon solar water heaters’, *Solar Energy*. Elsevier Ltd, 83(1), pp. 106–115. doi: 10.1016/j.solener.2008.06.005.

Koroneos, C. J. and Nanaki, E. A. (2012) ‘Life cycle environmental impact assessment of a solar water heater’, *Journal of Cleaner Production*. Elsevier Ltd, 37, pp. 154–161. doi: 10.1016/j.jclepro.2012.07.001.

Kumar, R. and Rosen, M. A. (2011) ‘Comparative performance investigation of integrated collector-storage solar water heaters with various heat loss reduction strategies’, *International Journal of Energy Research*, 35(13), pp. 1179–1187. doi: 10.1002/er.1764.

Kylili, A. *et al.* (2018) ‘Environmental assessment of solar thermal systems for the industrial sector’, *Journal of Cleaner Production*. Elsevier Ltd, 176, pp. 99–109. doi: 10.1016/j.jclepro.2017.12.150.

Laborderie, A. De *et al.* (2011) ‘Environmental Impacts of Solar Thermal Systems with Life Cycle Assessment’, in *World Renewable Energy Congress 2011 - 8-13 May 2011, Linkoping, Sweden*, pp. 3678–3685. doi: 10.3384/ecp110573678.

Lamnatou, C. *et al.* (2015) ‘The environmental performance of a building-integrated solar thermal collector , based on multiple approaches and life-cycle impact assessment methodologies’, *Building and Environment*. Elsevier Ltd, 87, pp. 45–58. doi: 10.1016/j.buildenv.2015.01.011.

Lenzen, M. (2001) ‘Errors in Conventional and Input-Output-based Life-Cycle Inventories’, *Journal of Industrial Ecology*, 4(4), pp. 127–148. doi: 10.1162/10881980052541981.

Lenzen, M. and Dey, C. (2000) ‘Truncation error in embodied energy analyses of basic iron and steel products’, *Energy*, 25(6), pp. 577–585. doi: 10.1016/S0360-5442(99)00088-2.

Majeau-Bettez, G., Strømman, A. H. and Hertwich, E. G. (2011) ‘Evaluation of process- and input-output-based life cycle inventory data with regard to truncation and aggregation issues’, *Environmental Science and Technology*, 45(23), pp. 10170–10177. doi: 10.1021/es201308x.

Martínez-Rocamora, A., Solís-Guzmán, J. and Marrero, M. (2016) ‘LCA databases focused on construction materials: A review’, *Renewable and Sustainable Energy Reviews*, 58, pp. 565–573. doi: 10.1016/j.rser.2015.12.243.

Martínez, E. *et al.* (2015) ‘Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study’, *Renewable Energy*, 74, pp. 237–246. doi: 10.1016/j.renene.2014.08.004.

Menzies, G. and Roderick, Y. (2010) ‘Energy and carbon impact analysis of a solar thermal collector system’, *International Journal of Sustainable Engineering*, 3(1), pp. 1–8. doi: 10.1080/19397030903362869.

Moncaster, A. M. and Song, J. Y. (2012) ‘A comparative review of existing data and methodologies for calculating embodied energy and carbon of buildings’, *International Journal of Sustainable Building Technology and Urban Development*, 3(1), pp. 26–36. doi: 10.1080/2093761X.2012.673915.

Moore, A. D. *et al.* (2017) ‘Life cycle assessment of domestic hot water systems in Australia’, *Renewable Energy*. Elsevier Ltd, 103, pp. 187–196. doi: 10.1016/j.renene.2016.09.062.

Piroozfar, P., Pomponi, F. and Farr, E. R. P. (2016) ‘Life cycle assessment of domestic hot water systems : a comparative analysis’, *International Journal of Construction Management*. Taylor & Francis, 16(2), pp. 109–125. doi: 10.1080/15623599.2016.1146111.

Pomponi, F. and Lenzen, M. (2018) ‘Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA', *Journal of Cleaner Production*. Elsevier Ltd, 176, pp. 210–215. doi: 10.1016/j.jclepro.2017.12.119.

Pomponi, F. and Moncaster, A. (2016) 'Embodied carbon mitigation and reduction in the built environment – What does the evidence say?', *Journal of Environmental Management*. Elsevier Ltd, 181, pp. 687–700. doi: 10.1016/j.jenvman.2016.08.036.

Pomponi, F. and Moncaster, A. (2017) 'Circular economy for the built environment: A research framework', *Journal of Cleaner Production*. Elsevier Ltd, 143, pp. 710–718. doi: 10.1016/j.jclepro.2016.12.055.

Rout, A., Sahoo, S. S. and Thomas, S. (2018) 'Risk modeling of domestic solar water heater using Monte Carlo simulation for east-coastal region of India', *Energy*. Elsevier Ltd, 145, pp. 548–556. doi: 10.1016/j.energy.2018.01.018.

Scottish Government (2017) *Draft Climate Change Plan: The draft third report on policies and proposals 2017-2032*.

Smyth, M., Eames, P. C. and Norton, B. (2000) 'Life Cycle Assessment of a Heat Retaining Integrated Collector/Storage Solar Water Heater (ICSSWH)', in *The Energy for the 21st Century World Renewable Energy Congress VI*. Brighton., pp. 1036–1040.

Smyth, M., Eames, P. C. and Norton, B. (2003) 'Heat retaining integrated collector / storage solar water heaters', *Solar Energy*, 75, pp. 27–34.

Swiatek, M., Fraisse, G. and Pailha, M. (2015) 'Stratification enhancement for an integrated collector storage solar water heater (ICSSWH)', *Energy and Buildings*. Elsevier B.V., 106, pp. 35–43. doi: 10.1016/j.enbuild.2015.07.005.

Tripanagnostopoulos, Y. *et al.* (2005) 'Energy, Cost and LCA Results of PV and Hybrid PV/T Solar Systems', *Progress in Photovoltaics: Research and Applications*, 13(January), pp. 235–250. doi: 10.1002/pip.590.

Tsilingiridis, G., Martinopoulos, G. and Kyriakis, N. (2004) 'Life cycle environmental impact of a thermosyphonic domestic solar hot water system in comparison with electrical and gas water heating', *Renewable Energy*, 29(8), pp. 1277–1288. doi: 10.1016/j.renene.2003.12.007.

Uctug, F. G. and Azapagic, A. (2018) 'Life cycle environmental impacts of domestic solar water heaters in Turkey: The effect of different climatic regions', *Science of the Total Environment*. Elsevier B.V., 622–623, pp. 1202–1216. doi: 10.1016/j.scitotenv.2017.12.057.

Uddin, S. and Kumar, S. (2016) 'Energy and Environmental Analysis of Domestic Solar Hot Water System in Asian Developing Country Context — Thailand', *Environmental Progress & Sustainable Energy*, 35(1), pp. 271–283. doi: 10.1002/ep.

Wang, Z. *et al.* (2015) 'Solar water heating: From theory, application, marketing and research', *Renewable and Sustainable Energy Reviews*. Elsevier, 41, pp. 68–84. doi: 10.1016/j.rser.2014.08.026.

Wheelhouse, P. (2017) 'Draft Scottish Energy Strategy: The Future of Energy in Scotland', (January). Available at: http://www.gov.scot/Publications/2017/01/3414/0.

Zambrana-Vasquez, D. *et al.* (2015) 'Environmental assessment of domestic solar hot water systems: A case study in residential and hotel buildings', *Journal of Cleaner Production*, 88, pp. 29–42. doi: 10.1016/j.jclepro.2014.06.035.