A method for a cradle-to-cradle life cycle assessment of integrated collector-storage solar water heaters

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Abstract. Solar thermal technologies are a potentially free and limitless source of energy. Due to the high demand for domestic hot water and the longer insolation periods during summer in Scotland, solar water heating (SWH) systems are a promising renewable energy technology. One of the systems within this technology is the integrated collector-storage solar water heater (ICSSWH). Existing research has predominantly focussed on the technical and economic aspects, with aims to reduce costs whilst maintaining operational performance. This begs the question, what are the true environmental costs of ICSSWH systems? Life cycle assessment (LCA) is an established methodology to evaluate the environmental performance of a product or a system across its life cycle. The aim of this paper is therefore to present an ICSSWH system from an LCA standpoint, also considering the current shift towards a more circular economy. Preliminary field data from a novel ICSSWH designed at Edinburgh Napier University will be presented. The paper will detail the data sources, impact assessment methods and software tools that will be used. Key outcomes from this research show that a holistic ICSSWH design, which considers whole-life implications, does not compromise efficiency and economic viability.

Keywords: Integrated collector-storage solar water heater; Life cycle assessment; Circular economy; Design for disassembly and reuse

1. Introduction

Given the global commitments to mitigate climate change and to limit global temperature rise to below 2°C from preindustrial levels [1], many countries are migrating to renewable energy sources with increasing interest in their research and development. Amid this zeal for zero/low carbon technologies there is a danger that large scale production of supposedly ‘green’ solutions will lead to their unsustainable growth, from a holistic life cycle viewpoint. Every product has associated embodied impacts that are necessary to produce, maintain, and dispose of it. For this purpose, a life cycle assessment (LCA) should be carried out to ensure that a product is environmentally sustainable, as well as technologically and economically feasible. This paper presents an LCA evaluation method of a unique integrated collector-storage solar water heater (ICSSWH) system under Scottish weather conditions, designed with the circular economy and reuse potential in mind.

2. Background

The consumption of energy in the UK is increasing across all sectors with the biggest change occurring in the domestic sector, which showed a 3.1% rise from 2015 to 2016 [2]. Scotland aims to provide 50% of total power output – in the forms of electricity, heat, and transport – by 2030 using renewable sources which would require the renewable energy contribution to triple compared to 2014 [3]. 53% of the
energy consumed in Scotland is in the form of heat, 13% of which is dedicated to domestic water heating [4]. This need for hot water, alongside the Scottish climate targets [5], calls for greater efforts to be made in renewable heat production. A potential contributing solution to this demand is the passive ICSSWH.

2.1. The ICSSWH system

Several studies have outlined the potential of ICSSWHs in climates similar to Scotland [6–8] and indeed the Scottish climate has been shown to be favourable for solar water heating due to its long heating season [9]. However, the literature surrounding these systems is largely focussed on improving performance and efficiency and reducing cost [10–13]. Relatively few studies focus on the environmental impact throughout the whole life cycle of the product, despite the importance of comparing the operational energy savings against the embodied energy to truly evaluate the sustainability of such systems.

The system under evaluation is a newly developed ICSSWH which offers improvements over its predecessors [9,14–16] and advantages over its competitors. Also, it can be disassembled to avoid any materials in the system being processed as waste at the end of its useful life thus reducing its life-cycle impacts and offering greater potential in terms of a circular economy. Figure 1 illustrates the basic collector-storage unit. During experimental testing, two variations of these collectors were mounted side-by-side. Each collector has the same dimensions, volume, absorber area, and collector material. They differ in that one collector has an internal baffle plate (“Baffled”) while the other has three elongated heat transfer fins (“Finned”). These configurations were chosen based on an extensive literature review surrounding ICS systems and the system is being compared against itself, under different design conditions, as opposed to commercially available solar systems. Three different design conditions have been considered for “Baffled” vs. “Finned”: basic system set-up; additional insulation applied to the top third of the absorber plate and; a night cover.

![Figure 1: The basic design concept of the ICSSWH under investigation.](image)

2.2. Life cycle assessment of solar water heaters

LCA is an environmental management tool that allows the environmental impact of a product to be quantified. The different stages that make up a complete LCA are shown in Figure 2. The final stage, D, considers a ‘cradle-to-cradle’ approach and transforms an LCA from a linear analysis to circular. This end-of-life stage appeals to the idea of a circular economy and analyses the recycle/reuse potential which can have a positive influence on LCA results; as utilising recycled over virgin materials greatly reduces the environmental impact [17]. A number of studies have focussed on the LCA of SWH systems, however, only one focusses on ICSSWH in the UK [18]. Therefore, there is a gap in the literature concerning the LCA of ICSSWH in the UK.

Following a systematic review of the literature, it is clear that the same methodology metric is rarely used making direct comparison, as well as repeatability, difficult. This is a common problem for LCAs in the built environment [19] and although many studies follow the ISO 14040 standard [20], they use different databases and analytical software. 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 [21]. The majority of studies also claim to conduct a cradle-to-grave LCA, which covers Stages A-C (Fig. 2). However, results are often presented as aggregated indexes, i.e. bulk calculations, not taking into account the truncation error inherent in many material databases [22]. The cradle-to-cradle LCA methodology applied in this paper is discussed in Section 4, where the materials and assembly of the ICSSWH under investigation are designed with the reuse/recycle potential as a strong consideration.

![Diagram](image)

Figure 2: Different stages of the building life-cycle, from cradle-to-cradle. Adapted from BSI [23].

3. Experimental results

Testing of the novel ICSSWH, under different design configurations, is ongoing and presented here is preliminary data. As such, a comprehensive LCA on this iteration of the collector has yet to be completed. A full annual test is desired to ensure as transparent and accurate an analysis as possible – once the energy contribution over a full year is known the carbon and energy savings can be calculated. Preliminary data will be presented to allow for a conservative estimation of annual contribution.

3.1. Energy calculations

The energy each ICSSWH can provide is derived from: 

\[ Q = mC_p\Delta T \]  

(1)

where, \( Q \) is the energy produced by the system, \( m \) is the mass of water in the system, \( C_p \) is the specific heat capacity of water, and \( \Delta T \) is the maximum bulk water temperature difference. Equation (1) enables calculation of the energy contribution from each system. Figures 3 and 4 give a snapshot of the energy that can be generated by the ‘Finned’ and ‘Baffled’ collector designs, respectively, under the different design conditions. This data is for a week period in autumn when insolation levels are lower than summer.

3.2. Estimated annual contribution

Based on a study monitoring the hot water consumption of 32 households in Edinburgh [24], a hot water demand of 50 l/person/day, at 55°C, is assumed. The average temperature of mains water is assumed to be 10°C, therefore, the temperature difference between the inlet water and required domestic hot water is 45°C. Under these assumptions and using equation (1), the energy required for a single occupancy household is approximately 2.6 kWh/day, 954 kWh/year. This is a rough estimation as hot water usage is heavily dependent on the lifestyle of the occupant, the time of year, and other external factors. Therefore, this value is being used as a conservative approach. Figure 5 shows the preliminary results of ongoing data collection. Partial experimental data collected from in-situ tests, with the systems being subject to a standardised domestic hot water profile [25], was used and the monthly energy contribution was extrapolated to give conservative estimations for annual performance. Once a full year of data has been collected, an in-depth LCA will be carried out using the following methodology and software tools.

4. LCA methodology

Given that a number of studies utilise the ISO 14040 methodology [20], that framework will also be adhered to in this work. An LCA should follow four main steps and the first is to identify the goal and
scope of the current study. This includes defining the system boundary, the functional unit (FU; to allow comparability and reproducibility), and the depth and breadth of the assessment. Secondly, the life cycle inventory (LCI) stage requires the necessary data collection. Thirdly, the life cycle impact assessment (LCIA) allows the quantification of potential environmental impacts based on the data collected for the LCI stage. Finally, an improvement analysis can be done to assess any possible solutions to the environmental issues that arise – for example, changes in production design, materials, energy use, waste management, reuse and recycling, etc.

4.1. Goal and scope

The goal of the present research is to determine the environmental impact of an ICSSWH under different design configurations (three testing phases as per Section 2.1). To make the system more attractive from an LCA point of view the absorber plate can be detached from the storage tank. The absorber plate is made of aluminium for its high thermal conductivity but it also has a much higher environmental impact. Therefore, the storage tank is made of stainless steel and the two are 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 with a circular economy ethos in mind.

4.1.1. Functional unit and system boundaries. The FU is defined as one ICSSWH unit designed to provide domestic hot water for a single occupancy dwelling, based on a consumption of 50 l/day, over a service life of 20 years. One FU includes the collector and associated fittings, detailed in Figure 2. Pipework to and from the collector and the surrounding insulation is excluded as it is assumed that this is already in place before the installation of the unit. This collector was designed for integration into the structural insulated panels (SIPs) used in warm roof construction. Therefore, the SIP itself provides the supporting frame and insulation for the back and sides of the collector.

The difference between the “Baffled” and “Finned” systems will have an impact across the whole life-cycle – Stage A will depend on the embodied carbon and energy associated with materials; Stage B
will depend on the operational performance throughout the useful life of the collectors; Stage C and D will depend on the recycle potential of the different materials. In terms of the useful life of the collector, a lifespan of 20 years is assumed. Transport was set at 50km as it is assumed that any travel is within a 50km radius, for example, manufacturer to site.

4.2. Life cycle inventory (LCI)

The LCI brings together all the materials used in the construction of the product and the creation of the FU, i.e. one ICSSWH unit providing hot water for one person. The data should show the quantity and total mass of each component, from which the percentage of the overall product weight can be calculated. The ISO 14040 standard [20] states that any component whose mass is less than 1% of the overall weight has a negligible effect in the analysis and can thus be neglected. However, to disaggregate the results as fully as possible and generate a more transparent and comprehensive LCA, a cut-off criteria of 0.5% on the mass will be applied in the analysis.

4.3. Life cycle impact assessment (LCIA)

Embodied energy is the energy expended throughout the systems useful life (i.e. from sourcing raw materials to the deconstruction of the FU) and is added to give a positive impact on the total energy, i.e. the energy needed. Operational energy, which is the useful energy generated by the FU during its useful life, is added to give a negative impact on total energy, i.e. the energy generated by the system. An LCIA of the ICSSWH FUs will be done for both operational and embodied energy, considering both a linear and circular economy to determine the positive (or negative) impact of the final supplementary stage of the LCA, Stage D.

Three main LCA methods exist in the built environment; process, input-output, and hybrid. Each has its own advantages and disadvantages with the hybrid analysis appearing to be the most accurate method [26]. However, as a hybrid LCA is a combination of process and input-output data it is a highly manual and time-consuming process [27]. Therefore, a process LCA is still a valid and viable method which is also recommended by the European and International Standards that are specifically developed for the construction sector [28].

The LCA tool that will be utilised in the analysis is OpenLCA v1.6.2 equipped with the Ecoinvent database v3.1, using global data. The impact assessment method that will be used to determine the embodied carbon is the CML Baseline (v4.4, January 2015) and for the embodied energy, the Cumulative Energy Demand (CED, v1.0.1, January 2015) will be used. These tools were adopted based on the types of analytical software and databases that are commonly used throughout European studies. The accuracy of the LCA relies on the integrity and applicability of the database used and they are often specific to geographic regions. Ecoinvent is considered to be a high quality database for European studies [29] and the CML tool provides robust and accurate results [30].

4.4. Improvement analysis

This final stage of the LCA process involves assessing the possibilities of improving any aspect of a product’s life-cycle in order to improve its environmental impact, by reducing the embodied carbon and energy. By disaggregating the LCI and LCIA and ensuring the LCA boundaries are well defined and comprehensive, areas of improvement can be pinpointed, such as inefficiencies in production design, materials and energy use or waste management/recycling [20]. In the current, ongoing work, potential contributions will be targeted as well as assessing the impact of the chosen heat retention methods on the operational carbon and energy savings.

5. Discussion and Conclusions

A process LCA approach to assess the newly developed ICSSWH designs was presented in this paper based on experimentally validated numerical data. By adopting this approach the authors found [31] that by taking a circular LCA approach and considering the recycle/reuse potential of the system, the newly designed ICSSWH had an embodied carbon saving of 47%. Using past data, operational carbon savings
equated to a carbon payback time of just 7 months, when replacing an electric system. The work presented here contributes a frame of reference to estimate the potential energy contribution for the current iteration of the system and outlines how LCA methodology can and should be used in this as well as similar projects.

6. References

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