Life Cycle Assessment of Domestic Hot Water Systems: A Comparative Analysis

Poorang Piroozfar[1,2*], Francesco Pomponi[1], Eric R.P. Farr[3]
[1]School of Environment and Technology, University of Brighton, Cockcroft Building, Brighton, BN2 4GJ, East Sussex, UK
[2]@BEACON (Advanced Technologies in Built Environment, Architecture and CONstruction), School of Environment and Technology, University of Brighton, Cockcroft Building, Brighton, BN2 4GJ, East Sussex, UK
[3]NewSchool of Architecture and Design, 1249 F Street, San Diego, CA 92101, USA

Abstract

On average, hot water is responsible for 18% of residential energy consumption and corresponding greenhouse gas (GHG) emissions. Several domestic hot water systems (DHWSs) are commonly used but their life cycle impacts are yet to be established comprehensively. This is due to those impacts varying significantly within the context and the system boundaries of the assessment. This article reports findings from a comparative cradle-to-grave life cycle assessment (LCA) of five DHWSs in the UK context.

Primary data acquired from a case study contributed to achieving accurate life cycle inventories that were then modelled in SimaPro through the ecoinvent database. Global Warming Potential (GWP) is the impact assessment method used. Amongst the five types, solar heater with electric backup appears to be the least damaging alternative. The study also reinforces the importance of adopting a cradle-to-grave approach if LCA results are to accurately reflect environmental impacts holistically and lead to better, more informed decisions.

Keywords: Domestic Hot Water Systems, Life Cycle Assessment, Life Cycle Inventory, Life Cycle Impact Assessment, Solar Heater

1. Introduction

Among building services a key role is played by the hot water system, which accounts for about 18% of the energy use of a home (EIA, 2013). As a consequence of global energy crisis in the late 1970s followed by concerns about the environment and global warming, there has been a continuous development of water heating technologies, mainly through gas and solar energy.

Solar energy is undoubtedly the most abundant energy source on Earth. If 0.1% of the solar radiation reaching the Earth's surface was converted into electric power, with 10% efficiency, it would generate four times the current global energy production (Thirugnanasambandam et al., 2010). However, 80% of the energy used today comes from non-renewable sources, bringing out a contradiction that should not exist (Thirugnanasambandam et al., 2010). Many countries are already using solar energy at a large scale in order to reduce their dependence on fossil fuels and cut their greenhouse gases (GHG) emissions. However, this renewable source has its downsides. Its availability is

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[*] Corresponding author; Email: a.e.piroozfar@brighton.ac.uk, Tel: +44(0)1273 642421

sporadic, and with current technologies this means it cannot meet the hot water demand throughout a whole day or a whole year. Therefore, hybrid technologies have been created to address this shortcoming, like the solar heating with electric support system. Research shows that switching from electric shower to these hybrid technologies can save up to 70% of energy used for providing hot water and up to 36% in total energy consumption of a residence (Altoé et al., 2012).

The figures above normally take into account primarily the use phase of the hot water systems. Although life cycle assessment (LCA) studies do exist with respect to domestic hot water systems (DHWSs), a cradle-to-grave comparative LCA in the context of the UK is missing, and this is the gap that this article aims to fill. Thus far, only two studies have focused on DHWSs in the UK (Allen et al., 2010; Greening & Azapagic, 2014), but both are chiefly related to solar hot water systems. Practical implications of this research will point towards the option(s) with lower environmental impacts, within the chosen system boundaries, thereby enabling designers, builders, suppliers and manufacturers to achieve better levels of environmental-friendliness and improve their awareness of the sustainability of the products they produce or specify. Such an outcome may in turn also contribute to higher awareness in the fields of building certification and rating, as well as energy policies, within the boundaries of this research. Additionally, as a secondary objective, this article shows the need for an enhanced clarity in the LCA field, discussing the results from the aforementioned cradle-to-grave perspective, and also a cradle-to-gate one. It is important to notice that although ISO standards clearly label cradle-to-gate studies as neither life cycle assessment nor life cycle inventories (ISO, 2006a), still too often, cradle-to-gate approaches bear the ‘life cycle’ connotation (Ip & Miller, 2012). This second objective also reinforces the necessity for enhanced clarity in LCAs of building components if environmental impacts are to be established holistically.

2. Literature Review

DHWS has been the focus of many studies. However, hardly ever have even two studies taken the same methodology or selected the same samples. Many researchers have taken different approaches in different context or in geographical settings, using different equipment configuration to approach LCA of DHWSs. In this section the leading research in the field is reviewed with an aim to set the scene for investigating further the possibilities, benefits and limitations of the approaches and to position the present work within the wider context of the research in this field.

2.1 Comparative studies

A study conducted to evaluate the environmental impact of water heating systems – using electric, gas and solar heaters – through LCA in domestic projects in Brazil shows that electric shower and solar system with gas heaters are the systems with the highest and the lowest impacts correspondingly (Taborianski, 2002). It is not however, unreasonable to assume that this is subject to significant change as the production process of solar heater systems has improved massively ever since this study was carried out.

LCA has been used in order to evaluate solar DHWSs and compare them with electricity and natural gas (Tsilingiridis et al., 2004) where environmental impacts associated with the production and utilization of solar DHWSs were assessed using Eco-Indicator 99.

The solar DHWS has a net gain of 696-2117 environmental impact points over electrical heaters, depending on the size of the system. The gain is shown to have been reduced by a factor of 4 when electricity is replaced by natural gas. The study also showed that among the materials used in solar DHWSs, steel and copper have major contributions to the overall impact.

It has been shown that the embodied energy component of the net energy requirement of solar and conventional hot water systems was insignificant in a study carried out in Melbourne, Australia, over a 10-year period, the typical warranty period of hot water systems (Crawford & Treloar, 2004). The solar hot water systems provided a net energy saving compared to the conventional systems after 0.5 and 2 years, for electricity- and gas-boosted systems respectively. This can be compared with Crawford et al. (2003) who found that compared to the conventional systems, solar systems provide net emissions savings after 2.5–5 years in Melbourne and after 2.5 years in Brisbane, depending on the auxiliary fuel and the life-cycle cost analysis which also revealed that the financial payback period for solar hot water systems is more than 10 years in Melbourne and around 10 years for an electricity-boosted system in Brisbane.

Though it might seem obvious that the environmental impacts of solar systems are always considerably less than that of the options that use electricity, to further confirm the findings by Koroneos and Nanaki (2012), it was shown in another study by Martinopoulos et al. (2013) that the solar hot water systems may have a lower impact than other heating options when considering the whole life cycle of the product, hence the systems with the best performance through their life cycle are not necessarily the same as those with less environmental impacts in production and manufacturing processes. This is due to much higher impact of substituted electricity in use phase which exceeds the small differences in the other stages. This research suggests

2.2 Solar Domestic Hot Water Systems (Solar DHWSs)

An LCA of a solar thermal collector, where an overall primary energy consumption of 11.5 GJ was calculated for extraction, production process, installation, maintenance, transports and disposal, suggests that 5% of this energy was used for manufacturing the collectors, 6% for transportation during different life cycle phases and the rest for production of raw materials (Ardente et al., 2005a). Ardente et al. (2005a) also show that the embodied energy associated with collector and water tank is the highest during the life cycle while by contrast energy and CO_2 payback times were less than 2 years confirming the great environmental convenience of this technology.

A sensitivity analysis study suggests that a great uncertainty exists regarding aluminium, copper, thermal fluid and galvanized steel, the dominant materials used in Solar Hot Water Systems (SHWSs), where other life cycle steps (transports, installation and maintenance) also cause large impacts (Ardente et al., 2005b). Despite high uncertainty, the study concludes that supposing a loss of efficiency up to 40%, it is estimated that, even in pessimistic scenarios, the energy and emission payback times are lower than 4 years. They argue for a positive qualitative judgement regarding the environmental performances of the collector that is not sensibly influenced by all the study uncertainties (Ardente et al., 2005b).

Life cycle analysis of a solar thermal system with thermochemical storage process, where an alternative efficient solar heating/cooling system based on a pair of salt-water endothermic/exothermic reaction was introduced, suggests that producing 1 GJ energy equates global warming potential of 6.3–10kg CO_2, acidification potential of 46.6–70g SO_2, eutrophication of 2.1–3.1g phosphate and photochemical oxidant of 0.99–1.5g C_2H_4 (Masruroh et al., 2006). The raw material acquisition and components manufacturing processes contribute 99% to the total environmental impacts. It is claimed that the new system provides a considerably better solution for reduction of negative environmental impacts by using solar energy more efficiently (Masruroh et al., 2006).

Another study of thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters in Nicosia, Cyprus suggests that apart from the economic and payback benefits, such solar water heater systems also offer benefits with respect to life cycle assessment of the systems (Kalogirou, 2009). The energy spent for the manufacturing and installation of the solar systems is recuperated in about 13 months, and it takes from a few months to 3.2 years (depending on the fuel and the particular pollutant considered) to compensate for the emissions pertaining to the embodied energy (Kalogirou, 2009).

Allen et al. (2010) carry out a study where they consider only a gas-fired boiler as the auxiliary heating system for SHWS, and further follow up their investigation where SHWS is installed alongside three auxiliary systems: a gas boiler, oil boiler, and electrical immersion heater. For these three systems they show that the SHWS would payback its embodied energy in 0.7–2.4 years, and its embodied carbon within 2 years. It was also shown that the use of aluminium has the greatest impact in the production process of the system. Their economic assessment asserts that the SHWS is currently uncompetitive, however, future prospects for reduced capital costs may suggest improved economic justification (Allen et al., 2010).

A longitudinal study of solar DHWSs use in Greece over 30 years (1978-2007) suggests that steady improvement in technology and production process of SHWSs has resulted in enhancement in their performance (Tsilingiridis & Martinopoulos, 2010). It also suggests that the climate change targets set by the Greek government have been exceeded by 76%, from 21.27 GWh_{el} in 1978 to 1513 GWh_{el} (2.4%) in 2007. They also investigate scenarios for future development in share of renewable solar energy in domestic hot water provision and speculate the potential capacity of installing new solar hot water systems which is then used to estimate the potential extents to which energy can be saved and CO_2 emissions can be reduced (Tsilingiridis & Martinopoulos, 2010).

Net energy analysis of domestic solar DHWSs in Ireland aimed at building on the real performance of installed systems in operation reviews those systems from a life cycle perspective (Hernandez & Kenny, 2012). The study confirms the findings of previous studies in that measured performance of domestic solar water heating systems can be lower than predicted. The study finds the energy payback based on the expected energy savings to be between 1.2 and 3.5 years, values comparable to previous studies but also suggests that the measured energy savings generally worsen the life cycle energy performance of this technology and thus increase the energy payback period. The study concludes that while there is a real potential for life cycle energy savings through solar DHWS installations, devising mechanisms to ensure proper design, installation and operation of systems are in place, is essential for this technology.

More recently a specific solar water heater was also studied taking into account the production process of raw materials – i.e. steel, glass, copper, aluminium, glass fibre and polyurethane insulators – the manufacturing process of the various parts of the system, and finally the assembly process (Koroneos & Nanaki, 2012). The emissions were calculated using the Eco-Indicator 99 and the main environmental impact of the system is due to eco-toxicity, more specifically acidification reaching up to 54%. The contribution to the Global Warming Potential (GWP) due to CO_2 emission has also been presented, although significantly lower at only 12% (Koroneos & Nanaki, 2012).

The LCA and LCC [Life Cycle Costing] of solar water heating systems has been studied for U.S. typical residential buildings in three different geographical locations, for two different types of solar collectors (flat-plate and evacuated-tube solar collectors), and two types of auxiliary systems (natural gas and electricity), where the flat-plate solar water heating systems using natural gas auxiliary heater was shown to have the best performance among all the types and at all locations (Hang et al., 2012). The energy and environmental payback periods are less than half of a year, and the life cycle cost payback vary from 4 to 13 years in different locations and for different configurations (Hang et al., 2012).

A recent study has been carried out to assess environmental impacts of solar DHWSs considering some impact categories and the energy pay-back time (EPBT) where 32 different types of SHWSs were considered (7 SHWS configurations, 4 different fuels for the auxiliary systems and 4 base cases without SHWSs) to meet the daily heating energy for hot water demand of two dwellings and 2 hotels, located in Aragón, Spain over a 20-year period (Zambrana-Vasquez et al., 2015). The results show that the use of biomass has some environmental benefits over other fuels in terms of kg CO_2. It is also shown that the use phase of the system is the one that contributes the most to the impact categories and that biomass has a higher value of EPBT. The paper suggests that final decision should be made based on a comparison between different benefits offered with regards to environmental impacts and EPBT.

Suffice to say, not all the studies have used same methodologies or have similar focus, hence different results. Some highlight solar systems as the most environmentally friendly system, whereas others prove otherwise. These results can differ, for example, due to availability of fossil fuels and electricity generation within the study region. The results also depend on the boundaries, limitations and scopes of the LCA in each study. Limitations of some studies, regardless of the validity and reliability of their results, render them as very case-specific researches where no or very little further generalization can be made. Some by contrast try to take into account the generalization factor but miss to provide full coverage of different systems. It is important to note that LCA studies for obvious reasons are bound to be carried out within a particular geographical location, and the current study is no exemption. Given these inevitable contextual boundaries, this research attempts to take all the measures to ensure objective results are reached that are robust for validity and reliability tests.

3. Research Methodology and Design

This research uses a single-case study with multiple-unit of analysis to investigate different DHWSs in a live building project. Although primarily considered qualitative, case study research utilizes both qualitative and quantitative research methods (Bryar, 2000). In case of current research which is heavily relying on quantitative data in its different units of analysis, as a case study it is still believed to belong to a constructivist paradigm (Stake, 1995). Yin (2009, p.38) strengthens the methodological legitimacy of case studies by arguing that a “fatal flaw in doing case studies is to conceive of statistical generalization as the method of generalizing the results of the case study” because cases are not sampling units and should be treated as experiments (Tsang, 2014). The primary strength of case study research is its reliance on data enquiry from different sources and multiple data collection techniques. This increases the validity of findings (Newman & Ridenour, 2008) hence the approach of this research, where tested and approved methods for enquiring and analysing data commonly utilized in LCA through its two middle stages, namely life cycle inventory (LCI) as data acquisition, and life cycle impact assessment (LCIA) as data analysis, have been employed.

A Life Cycle Assessment (LCA) is the compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006a, 2006b). System boundaries generally span from extraction of raw materials to the end of production stage (cradle-to-gate study), or to final disposal of the product when it comes to end of its service life (cradle-to-grave study). The methodological framework consists of four phases; as seen in Figure 1.

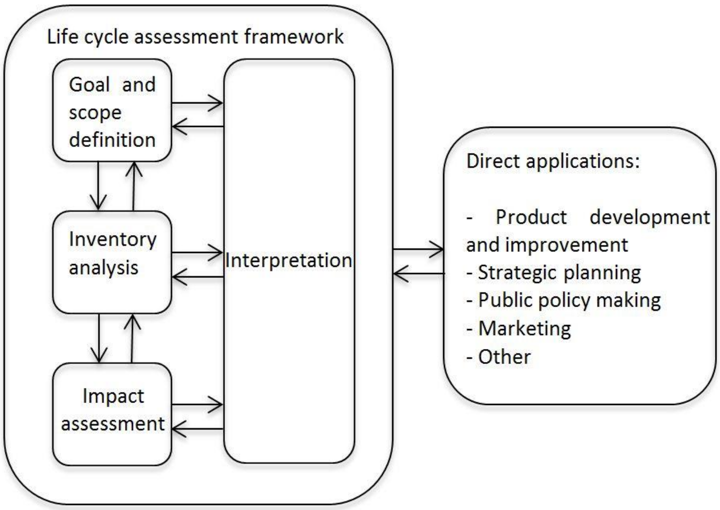

Figure 1 - Life Cycle Methodological Framework (ISO, 2006a)

The first phase deals with defining the goal and the scope of the study, the system boundary, the functional unit (FU) to ensure comparability and reproducibility, the level of detail, as well as depth and breadth of the assessment. The LCI phase involves the necessary data collection phase. Finally, during LCIA phase, the significance of potential environmental impacts is quantified using the results from the LCI stage.

3.1 Goal and Scope

The goal of this assessment is to gauge the environmental impacts of different types of residential water heating systems in order to identify:

a) the contribution of different life cycle stages within each system studied, thus highlighting the phases which bear the highest environmental loads, and
b) the system with the lowest environmental impacts (i.e. the least damaging alternative)

The focus is on the amount of GHGs emitted during the entire life cycle. Such an impact category addresses climate change related impacts and the method used is the GWP indicator over a period of 100 years (IPCC, 2013). The LCA tool used throughout this study is

SimaPro 8.0.3.14 equipped with ecoinvent 2013, the world's leading double peer-reviewed database with consistent and transparent, up-to-date LCI data (Weidema et al., 2013).

The study is conducted for a typical four-storey multi-family domestic building. More specifically, a modular building has been chosen (Figure 2), defined as a construction method where individual modules, stand-alone or assembled together, make up larger structures (MBI, 2009).

Figure 2 -View from the construction site and rendering of the modular building

The reason for such a choice is that modular buildings are quickly gaining momentum in the AEC industry due to "fast delivery, reduced environmental impact, ease of relocation, low-cost reconfiguration, and enormous flexibility" (MBI, 2009, p. 2). The case considered in here consists of 16 apartments and is supposed to be located in city of Brighton and Hove, South East England. The other reasons for selection of this case study include:

- Global dimensions of the design scheme which make it suitable to be used above and beyond its supposed geographical location in South East England

- Its suitability for modern contemporary life style
- Its clear spatial layout which makes the intended M&E easy to implement and the swap between the systems easy with no further need for major additional intervention which may bear unnecessary impacts on LCA
- Offering possibilities to accommodate the intended technologies (on the flat roof)
- The legibility, transparency and ease of the structural system proposed here (Figure 2b), makes the end product equally fit for purpose for accommodating different standards and specifications ranging from social housing to high-end boutique flats with no impact on the selected hot water system.

As highlighted in the literature review, the most used hot water systems are electric and gas boilers, solar collectors and instantaneous systems (electric shower and passage heater with gas), hence they are the ones selected for evaluation in this study.

3.2 Functional Unit, Systems, and System Boundaries

The functional unit (FU) was defined as the production of 392448000 litres of heated water with a temperature of at least 37 °C. Although older studies suggest shorter periods for an average shower time, a recent study by behavioural psychologists at Unilever UK and Ireland suggests that “the average shower is eight minutes long and uses nearly as much energy and water as a bath” (Unilever, 2011). For the specific purpose of the current study and to stay within a safe margin, it was assumed that a shower will last for 7 minutes with a 0.20 l/s flow rate and 4 showers a day (1 shower/day/inhabitant and 4 people living in each of the 16 apartments) over 20 years. The reference flow is the mass of each material used to provide the determined functional unit.

In accordance with LCA methodology, this is a cradle-to-grave study, which means that systems boundaries include the raw material extraction, materials production, supply (transport), use phase and disposal/end-of-life treatment. Use phase plays a key role in this analysis, since the systems work significantly differently from one another. The process of assembling parts of the heat units in the various manufacturing plants and the installation in-situ will not be taken into account due to the lack of good quality data. As a service life, it is assumed that the systems last for a 20-year period (where, in addition, replacement of parts for some systems at shorter intervals may be necessary). Transport distances are calculated based on a market research. For each material or component, the nearest extraction or production plant to the building site has been determined.

Full details of the following systems considered for this study are provided in the supporting material available online and linked to this article (Figures S2 through to S5, and Tables S1 through to S10):

- Electric shower
- Passage heater with gas
- Solar heater with electric backup
- Electric boiler; and
- Gas boiler

4. Life Cycle Inventory

Water heater units form the major component of DHWSs. However, such systems are not merely limited to water heaters. Pipes, records, valves and accessories also form part of the system. Thus, the LCA for these systems is more complex, involving multiple devices with different types of materials.

The amount of each material/component in terms of mass (kg) was taken into account in order to calculate the environmental loads of the whole life cycles of the nominal equipment which were selected for the purpose of this study.

4.1. Electric shower

7500W Triton Seville (Figure) was selected as the electric shower, because it has a low response time to provide good quality shower and has a high safety rate.

When an electric shower is used there is a significant increase in the energy demand. Thus, there is a need for a three-phase power supply and the use of a larger diameter for copper cables and conduits. Furthermore, it was necessary to provide a specific circuit for the electric shower. The representation, specification and quantification of the mechanical electrical and plumbing (MEP) components is given in Figures S3 and S4, and Tables S1 and S2 (online supporting material).

It is worth mentioning that much more ore at extraction phase is needed than the actual amount used in the final product since there is a significant loss due to quality of raw material which results in waste.

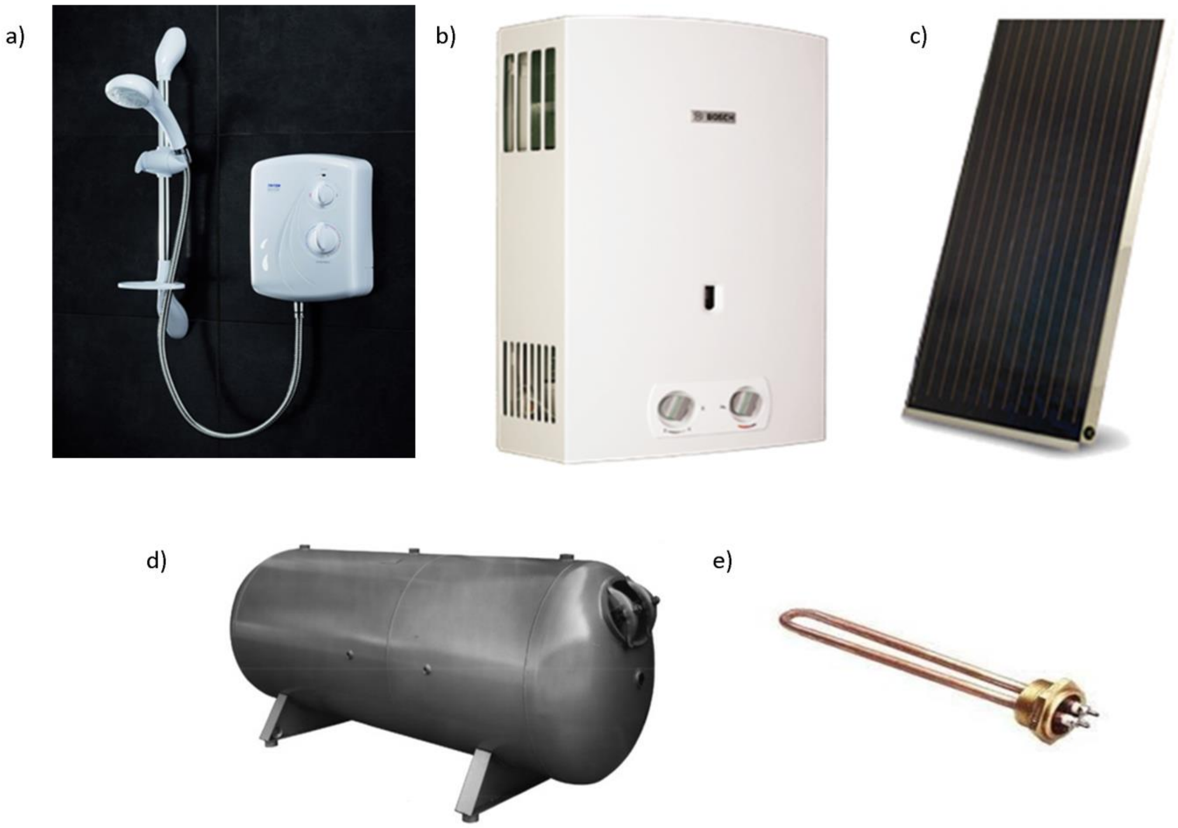

Figure 3 – Pictures of some components of the systems assessed

Supply is estimated as the total amount of components required for the system installation (around 1726kg) to arrive from factories within an average of 270km distance, resulting in 1.726x270 = 466tkm.

By multiplying the amount of hours of the electric shower use by its power, the energy demand for the use phase of the product can be calculated:

$$7.5kW \times \left(\frac{\left(7 \min \times \frac{60s}{min}\right)}{\frac{3600s}{h}} \right) \times 64 \ \frac{showers}{day} \times 365 \ \frac{days}{year} \times 20 \ years = 408800 \ kWh$$

Considering an efficiency of 80%, the demand is:

$$\frac{408800 \text{ kWh}}{0.8} = 511000 \ kWh \ of \ low \ voltage \ at \ grid$$

The environmental impact depends on the percentage of production of the electricity plant types in the country. SimaPro has a database for Great Britain, so national figures are taken into account.

Same principles apply to disposal scenarios. SimaPro has a database with the waste scenario for England, so, 100% of the production was disposed of according to that scenario.

Table 1 shows the electric shower inventory:

Table 1 - Electric shower inventory

Extraction

Material	**SimaPro**	**Weight (kg/u)**
Copper	Copper, primary, at refinery	3883.13
Iron	Iron ore, 46% Fe, at mine	142
Nickel	Nickel, 99.5%, at plant	64
Chromite	Chromite, ore concentrate, at beneficiation	25.6

Transformation

Material	**SimaPro**	**Weight (kg/u)**
Electrolytic copper	Copper, concentrate, at beneficiation	33.7
Iron ore beneficiation	Iron ore, 65% Fe, at beneficiation	85.5
Steel mill	Steel, low-alloyed, at plant	85.5
Petroleum refining for PVC	PVC (suspension polymerization) E	13673.8
Electrolytic nickel	Nickel, secondary, from scrap recycling	25.6
Chrome	Chromium, at regional storage	0.82
Resistor alloy	Iron-nickel-chromium allow, at plant	0.48

Manufacturing

Process	**SimaPro**	**Weight (kg/u)**
Copper wires	Wire drawing, copper	30
PVC moulding	Injection moulding	7056

Resistor moulding	Metal working machine operation	0.48
Supply		
Transport	**SimaPro**	**tkm**
Electric shower	Transport, lorry 16-32t, EURO3	6.4
Copper wires	Transport, lorry 16-32t, EURO3	8.6
PVC	Transport, lorry 16-32t, EURO3	451
Use phase		
Input	**SimaPro**	**kWh**
Electricity	Electricity, low voltage, at grid/GB	511000
Disposal scenario		
Type	**SimaPro**	**Allocation**
England	Waste scenario/Eng	100%

4.2. Passage heater with gas

With a water flow of 12 l/min, Bosch Comfort Line GWH 250 B ND (**Error! Reference source not found.**) was selected as a nominal product for passage heater with gas for its suitability, convenience and popularity for small residential buildings. Full details are available in Tables S3 and S4 (online supporting material).

Chlorinated polyvinyl chloride (CPVC) pipes have been assumed as hot water pipes in order to reduce the cost of components. Metal pipes were used just for the supply of gas to the equipment.

In this system, natural gas was assumed as the energy source for the heater. As it does not use electricity, the power supply can be single-phase wiring and with smaller diameters.

Supply is estimated as the total amount of components needed for the system installation (around 1426kg) coming from factories within an average of 280km distance, adding up as 1.426x280 = 400tkm.

The heater maximum gas consumption is 2m^3/h. By multiplying the amount of hours of use by its consumption, the energy demand for the use phase of the product can be calculated:

$$2\frac{m^3}{h}\left(\frac{\left(7\min\times\frac{60s}{min}\right)}{\frac{3600s}{h}}\right)\times 64\,\frac{showers}{day}\times\,365\,\frac{days}{year}\times 20\,years=\;109013\,m^3\,of\ natural\ gas$$

Considering that each m^3 of natural gas produces 38.7 MJ of energy, the demand is:

$$109013\,m^3\;\times 38.7\,\frac{MJ}{m^3}=4218803\,MJ\,of\ heat\ from\,natural\ gas$$

Table 2 shows inventory for the passage heater with gas supply.

Table 2 – Passage heater with gas inventory

Extraction

Material	SimaPro	Weight (kg/u)
Copper	Copper, primary, at refinary	10678.6
Iron	Iron ore, 46% Fe, at mine	760
Zinc	Zinc, primary, at regional storage	218
Alumina	Alumina, at plant	15.68
Bauxite	Bauxite, at mine	39.36

Transformation

Material	SimaPro	Weight (kg/u)
Electrolytic copper	Copper, concentrate, at beneficiation	92.7
Brass	Brass, at plant	7.52
Iron ore beneficiation	Iron ore, 65% Fe, at beneficiation	450.6
Steel mill	Steel, low-alloyed, at plant	450.6
Petroleum refining for PVC	PVC (suspension polymerization) E	12306.4
Aluminium	Aluminium, primary, liquid, at plant	7.84

Manufacturing

Process	SimaPro	Weight (kg/u)
Copper wires	Wire drawing, copper	82
PVC moulding	Injection moulding	6350
Metals inside the heater	Metal working machine operation	187.2

Supply

Transport	SimaPro	tkm
Gas heater	Transport, lorry 16-32t, EURO3	50
Copper wires	Transport, lorry 16-32t, EURO3	22
PVC	Transport, lorry 16-32t, EURO3	328

Use phase

Input	SimaPro	MJ
Natural gas	Heat, natural gas, at boiler modulating<100kW	4218803

Disposal scenario

Type	SimaPro	Allocation
England	Waste scenario/Eng	100%

4.3. Solar heater with electric backup

Conventional thermosyphon was selected for solar heater with electric backup. It requires no water circulation pump. A thermal reservoir, a 1000-litre water tank located at least 0.5m above the solar panels on the roof of the building, is also part of the system. Full details are available in Figure S5 and Tables S5 and S6 (online supporting material). The selected system consists of 10 SunMaxx TitanPowerPlus-SU2 solar panels (Figure 3c) equipped with a Parker Horizontal Storage Tank A-1000-HT (Figure 3d).

This system requires a device to drop pressure between the water tank and the thermal reservoir, in order to have a pressure difference at the entrance of the reservoir and avoid a backflow of hot water into the cold water reservoir. Copper pipes were used for the hot water network, since in the solar system the hot water temperature can exceed the maximum temperature that a plastic pipe can operate under.

For the solar heating, flat plate collectors were used with a total area of 20m^2. The radiation is captured during the sunny hours of a day, converted into heat then transferred to the water, which is stored for use when necessary. In situations with several days without sunlight or low irradiation, an auxiliary heater that uses electricity is considered as backup. This heater consists of a resistor located inside the hot water storage tank.

A 5000W resistor (Figure 3e was selected, since the 1000l hot water tank proposed in this study requires such relatively high power. Thus, the electricity consumption during the use stage of the solar heating will be used only by the resistor to cover the solar energy fluctuation during a specific period of time.

Because of the increase in the power used by the system, the power supply will be three-phase and it was necessary to add a circuit to feed the resistor off the hot water tank.

Supply is estimated as the total amount of components needed for the system installation (around 2000kg) to be brought in from factories within an average of 280km distance, giving 2x280 = 560tkm as a result.

For the use phase the online Valentin Software was used (ValentinSoftware, 2014). For Brighton, 20m² of collectors with 30° slope, facing south generates around 21686kWh per year, which is more than the water heating demand. However during winter or cloudy days, the resistor will be needed to meet the hot water demand. Assuming that the solar heater covers 80% of the showers, the resistor is still needed to cover 20% (Taborianski, 2002). So, by multiplying the number of use hours of the system by its power, the energy demand for the use phase of the product can be calculated as follows:

$$5kW \times \left(\frac{\left(7\,\mathrm{min} \times \frac{60s}{min}\right)}{\frac{3600s}{h}}\right) \times 64\,\frac{showers}{day} \times 365\,\frac{days}{year} \times 20\,years \times 20\% = 54506\,kWh$$

Considering an efficiency of 80%, the demand is:

$$\frac{54506\ \mathrm{kWh}}{0.8} = 68133\ kWh\ of\ low\ voltage\ at\ grid$$

Table 3 shows the solar heater inventory:

Table 3 – Solar heater inventory

Extraction

Material	SimaPro	Weight (kg/u)
Copper	Copper, primary, at refinery	31634.4
Iron	Iron ore, 46% Fe, at mine	59.36
Cassiterite	Tin, at regional storage	167.5
Alumina	Alumina, at plant	170.2
Bauxite	Bauxite, at mine	425.5

Transformation

Material	SimaPro	Weight (kg/u)
Electrolytic copper	Copper, concentrate, at beneficiation	274.6
Iron ore beneficiation	Iron ore, 65% Fe, at beneficiation	3.56
Steel mill	Steel, low-alloyed, at plant	3.56
Petroleum refining for PVC	PVC (suspension polymerization) E	10340.3
Glass wool	Glass wool mat, at plant	33
Glass	Flat glass, uncoated, at plant	101
Expanded polyethylene	Fleece, polyethylene, at plant	23.8
Aluminium	Aluminium, primary, liquid, at plant	85.1

Manufacturing

Process	SimaPro	Weight (kg/u)
Copper wires	Wire drawing, copper	15
PVC moulding	Injection moulding	5335.5
Copper pipes	Copper product manufacturing	250

Supply

Transport	SimaPro	tkm
Solar panels	Transport, lorry 16-32t, EURO3	95.2
Copper wires	Transport, lorry 16-32t, EURO3	4.2
Copper pipes	Transport, lorry 16-32t, EURO3	70
Storage tank	Transport, lorry 16-32t, EURO3	112
PVC	Transport, lorry 16-32t, EURO3	280

Use phase

Input	SimaPro	kWh
Electricity	Electricity, low voltage, at grid/GB	68133

Disposal scenario

Type	SimaPro	Allocation
England	Waste scenario/Eng	100%

4.4. Electric boiler

The same auxiliary system as explained in the above option was selected for this option too, that is a thermal reservoir with 1000 litres Parker Horizontal Storage Tank A-1000-HT (Figure 3d) with a 5000 W resistor (Figure 3e).

Again, the system requires a device for pressure regulation between the water tank and the thermal reservoir, copper pipes were used for hot water network and the power supply will be three-phase, with a specific circuit to feed the resistor for the hot water tank. Full details are given in Tables S7 and S8 (online supporting material).

Supply is estimated as the total amount of components needed for the system installation (around 1568kg) to be transported from factories within an average of 255km distance, which will result in 1.568x255 = 400tkm.

Assuming that the boiler works for 4 hours a day, multiplying the hours of its use by its consumption, the energy demand for the use phase of the product can be calculated at:

$$5kW \times 4\,\frac{hours}{day} \times 365\,\frac{days}{year} \times 20\,years = 146000\,kWh$$

And considering an efficiency of 80%, the demand will be:

$$\frac{146000\ \mathrm{kWh}}{0.8} = 182500\,kWh\,of\,\,low\,\,voltage\,\,at\,\,grid$$

Table 4 shows the electric boiler inventory:

Table 4 – Electric boiler inventory

Extraction

Material	**SimaPro**	**Weight (kg/u)**
Copper	Copper, primary, at refinery	20781.9
Iron	Iron ore, 46% Fe, at mine	35.5
Alumina	Alumina, at plant	105.6
Bauxite	Bauxite, at mine	221.8

Transformation

Material	**SimaPro**	**Weight (kg/u)**
Electrolytic copper	Copper, concentrate, at beneficiation	180.4
Iron ore beneficiation	Iron ore, 65% Fe, at beneficiation	2.13
Steel mill	Steel, low-alloyed, at plant	2.13
Petroleum refining for PVC	PVC (suspension polymerization) E	10340.3
Expanded polyethylene	Fleece, polyethylene, at plant	23.8
Aluminium	Aluminium, primary, liquid, at plant	52.8

Manufacturing

Process	**SimaPro**	**Weight (kg/u)**
Copper wires	Wire drawing, copper	15
PVC moulding	Injection moulding	5335.5

Copper pipes	Copper product manufacturing	150
Supply		
Transport	**SimaPro**	**tkm**
Copper wires	Transport, lorry 16-32t, EURO3	4.2
Copper pipes	Transport, lorry 16-32t, EURO3	42
Storage tank	Transport, lorry 16-32t, EURO3	112
PVC	Transport, lorry 16-32t, EURO3	280
Use phase		
Input	**SimaPro**	**kWh**
Eletricity	Electricity, low voltage, at grid/GB	182500
Disposal scenario		
Type	**SimaPro**	**Allocation**
England	Waste scenario/Eng	100%

4.5. Gas boiler

The system and considerations are the same as the electric boiler, but instead of using a resistor as a heating source, the water in the tank will be heated by a natural gas boiler.

The heater's maximum gas consumption is 2m³/h. So, under the assumption that the boiler works for 4 hours a day, multiplying the number of use hours by its consumption, the energy demand for the use phase of the product can be calculated:

$$2\frac{m^3}{h} \times 4\,\frac{hours}{day} \times 365\,\frac{days}{year} \times 20\,years = \ 58400\,m^3\,of\ natural\ gas$$

Considering that each m³ of natural gas produces 38.7 MJ of energy, the demand is:

$$58400\,m^3\ \times 38.7\,\frac{MJ}{m^3} = 2260080\,MJ\ of\ heat\ from\ natural\ gas$$

Table 5 shows the gas boiler inventory.

Table 5 – Gas boiler inventory

Extraction

Material	**SimaPro**	**Weight (kg/u)**
Copper	Copper, primary, at refinery	19561.6
Iron	Iron ore, 46% Fe, at mine	35.5
Alumina	Alumina, at plant	105.6
Bauxite	Bauxite, at mine	221.8
Transformation		
Material	**SimaPro**	**Weight (kg/u)**

Electrolytic copper	Copper, concentrate, at beneficiation	170
Iron ore beneficiation	Iron ore, 65% Fe, at beneficiation	2.13
Steel mill	Steel, low-alloyed, at plant	2.13
Petroleum refining for PVC	PVC (suspension polymerization) E	10340.3
Expanded polyethylene	Fleece, polyethylene, at plant	23.8
Aluminium	Aluminium, primary, liquid, at plant	52.8
Manufacturing		
Process	**SimaPro**	**Weight (kg/u)**
Copper wires	Wire drawing, copper	15
PVC moulding	Injection moulding	5335.5
Copper pipes	Copper product manufacturing	150
Supply		
Transport	**SimaPro**	**tkm**
Copper wires	Transport, lorry 16-32t, EURO3	4.2
Copper pipes	Transport, lorry 16-32t, EURO3	42
Storage tank	Transport, lorry 16-32t, EURO3	112
PVC	Transport, lorry 16-32t, EURO3	280
Use phase		
Input	**SimaPro**	**MJ**
Natural gas	Heat, natural gas, at boiler modulating<100kW	2260080
Disposal scenario		
Type	**SimaPro**	**Allocation**
England	Waste scenario/Eng	100%

5. Life Cycle Impact Assessment and Interpretation of Results

The embodied and operational carbon dioxide equivalent values of all the assessed options are indicated in Table 6, in the form of kg CO_{2e} and also as percentages of the total impacts for each life cycle stages.

Five main life cycle stages have been identified other than the use phase, which are: 1) extraction of the raw materials, 2) transformation, 3) subsequent manufacturing, 4) supply, and finally 5) disposal. These form what eventually accounts for the embodied energy and embodied carbon.

Amongst those five, manufacturing is the one with more consistent share across the five systems. To the contrary, extraction and disposal vary greatly depending on the specific DHWS. Finally, transformation presents some variation as well—although in a more limited range.

Table 6 - Numerical Results of GWP impacts of different life cycle stages for each of the DHW system assessed

	Assessed DHW Systems									
Life Cycle Stages	**Electric Shower**		**Passage heater with gas**		**Solar heater with electric backup**		**Electric boiler**		**Gas boiler**	
	kg CO_{2e}	%	kg CO_{2e}	%	kg CO_{2e}	%	kg CO_{2e}	%	kg CO_{2e}	%
Extraction	12885.3	3.1%	34192.4	8.36%	102204	50%	65280	27.2%	61411	21.7%
Transformation	37279.8	8.9%	34356	8.4%	29376	14.4%	28800	12.0%	28866	10.2%
Manufacturing	9424.2	2.3%	8711.7	2.1%	7568.4	3.7%	7392	3.1%	7386.3	2.6%
Supply	208.5	<<1%	207.5	<<1%	204	<<1%	96.2	<<1%	113.2	<<1%
Use	349863	84%	321065	79%	46512	22.8%	125040	52.1%	172347	60.9%
Disposal	7631.1	1.8%	10470.4	2.6%	18217.2	8.9%	13392	5.6%	12876.5	4.6%
Totals	417291.9	100%	409003	100%	204081.6	100%	240000.2	100%	283000	100%

This specific detail of the results can be of useful in understanding, within each system, which life cycle stage is worth further investigation and closer attention in order to minimize the overall GHG emissions.

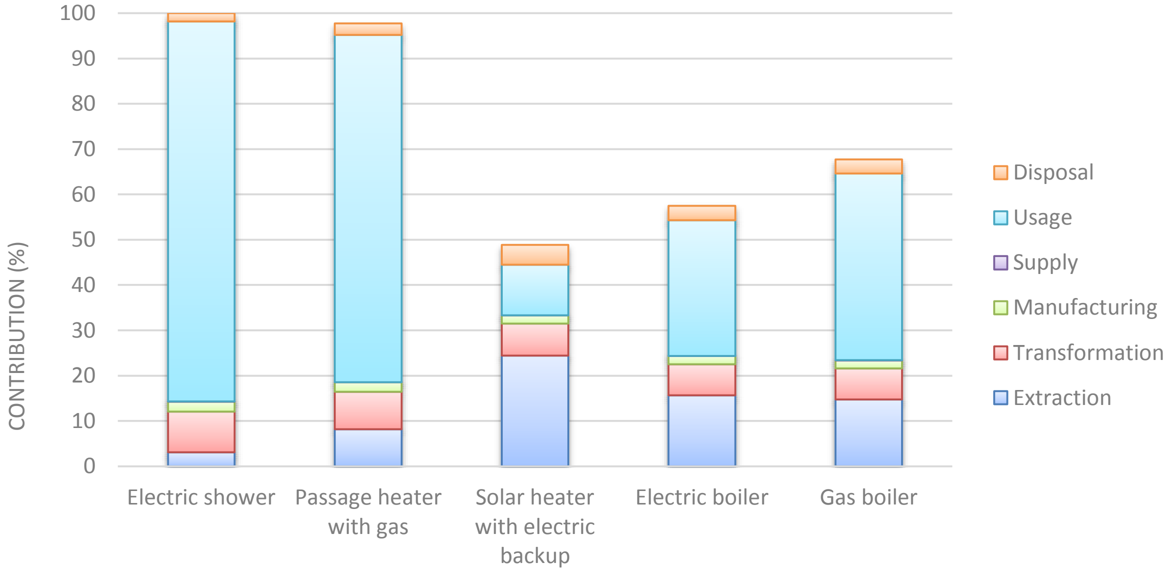

Figure 4 - Normalized percentage values of the impacts of different life cycle phases for the DHW systems considered

Numerical values in Table 6 have been reported in the form of bar charts in Figure 4, where percentages have been normalized. Results show that electric shower is the DHWS with highest environmental impact (benchmarked at 100%), followed by passage heater with gas (98%), gas boiler (68%), electric boiler (57%) and finally solar heater with electric backup (49%). Therefore, given the assumptions, the system boundary, and the methodical choices of this study, solar heater with electric backup is the best option among the five to minimize adverse climate change impacts.

To contextualize findings from this research within other published studies, it is worth noting that Tsilingiridis et al. (2004) report solar heater as the best option, followed by gas and then electric devices whereas Taborianski and Prado (2004) indicate the electric shower as the most impacting system, followed by the solar system and eventually gas heaters as the best option. Both studies show different results from the present one. That is mainly due to the type of construction examined in the studies: housing vs. non-domestic buildings, and the geographical locations: Greece, and Brazil vs. Brighton. The climate, the energy mix, the availability of gas and other aspects are different in each country, thus making great differences in the final results.

However, it is extremely worth noting that such results heavily depend on the perspective used, which in this article is – once again – a cradle-to-grave. Indeed, had it been adopted a cradle-to-gate perspective results would have been completely different, as it is easy to spot from Figure 4.

In that case the solar system is the one that impacts the most, followed by the electric boiler with 73% of the solar system, then the gas boiler with 70%, the passage heater with gas with 56% and the electric shower with 43%. If DHW systems assessed were ranked from 1st to 5th the ranking from the cradle-to-gate would be the exact opposite of that from the cradle-to-grave study (Table 7).

Table 7 - Ranking of the five DHWSs assessed according to the LCA and the cradle-to-gate perspective

DHWS	Cradle-to-gate ranking	Cradle-to-grave ranking (LCA)
Electric shower	1st	5th
Passage heater with gas	2nd	4th
Gas boiler	3rd	3rd
Electric boiler	4th	2nd
Solar heater with electric backup	5th	1st

By observing Table 6 and Figure 4 it can be seen that the use phase – with its all preliminaries, assumptions, different life styles and personal or social norms and standards involved – play a major role in determining how environmentally friendly a DHWS is. Such a finding is in line with, for instance, those of Martinopoulos et al. (2013), highlighting that the predominant role of the use phase is true almost regardless of the context, despite that final results do seem to be context-dependant as discussed above with respect to Tsilingiridis et al. (2004) and Taborianski and Prado (2004).

Such a difference in the two assessments reinforces the importance of adopting a cradle-to-grave perspective when conducting an LCA as recommended in ISO standards (ISO, 2006a). In other words, all stakeholders in the AEC industry including manufacturers, suppliers, decision makers, legislators, developers, designers, contractors, clients and end users as well as those involved in post-occupancy phases involved in operation and maintenance and those in demolition and disposal/recycling/reuse phases should take a second look at how the environmental credentials of a building component or product has been carried out. In fact, a cradle-to-gate study may well lead to choose the most damaging alternative despite the probably genuine aim of identifying the least damaging one.

Due to the different distribution of environmental burdens within the assessed DHWSs it does make sense to think of environmental payback periods (EPBP). For instance, in comparing the electric shower and the solar heater (worst and best options from a cradle-to-grave perspective), the greater embodied carbon of the latter is compensated by its operational carbon savings over the former just after 29.7% of the systems' lifespan. And with a service life of 20 years, it means that in just under 6 years, the solar heater will have paid back its greater embodied carbon and the net operational savings start with added benefits to the environment for the remainder of the system's service life.

Although contexts greatly vary from one study to the other, such value of EPBP is in line with other published figures of comparative studies involving solar hot water systems (e.g. Crawford et al., 2003).

6. Conclusions

The hot water system has a significant impact on energy consumption of a building. When well designed and controlled, it can play a major role in savings in energy and CO_2 emissions. This research aimed to cast light on how to select a DHWS amongst five most commonly used types by using LCA to identify the least damaging alternative in terms of climate change related impacts through the global warming indicator chosen as the assessment method.

Within the contextual boundaries of this research, results indicate the solar heater with electric backup as a better option than all other ones – namely, electric shower, passage heater with gas, electric boiler and gas boiler. The advantage is achieved in the use phase of the system. While electricity and natural gas have a very high impact for the other four options, the solar heater takes profit of the solar irradiation to heat the water, as very clean and renewable source of energy for providing domestic hot water. However, findings of this research do not necessarily mean that a solar heater is always the best option. Firstly, it was analysed as a particular equipment in a particular building and in a specific site. When analysing, for instance, a residential house in Greece or an office building in Brazil, results could be significantly different. Secondly, economic viability of the considered options has not been assessed within this research in spite of financial considerations often impacting on if not driving the decisions in the choice of building products and systems. However, the trends observed within the cradle-to-gate and cradle-to-grave perspectives could potentially reflect the investment vs. running costs trade-offs. As such, solar systems tend to be more expensive as an investment (with higher initial costs) but with significant saving during use phase. However, this represents a topic that deserves a research on its own right through, for instance, Life Cycle Costing (LCC).

Although maximum care has been taken in order to ensure that a robust and valid research has been carried out, the use of estimation rather than primary data on the use phase (i.e. real consumption) and the lack of uncertainty analysis of the results surely represent some limitations of this study and, therefore, constitute interesting avenues for further research. Furthermore, different water heating systems, different buildings and different locations can be analysed in order to create a database for the best option for each specific situation.

The findings from this research can be practically useful to the stakeholders in the AEC industry—including manufacturers, suppliers, decision makers, legislators, developers, designers, contractors, clients and end users as well as those involved in post-occupancy phases involving operation and maintenance and those active in demolition and disposal/recycling/reuse phases—to understand the life cycle climate change impacts of five commonly used DHWSs holistically. Further, the breakdown of results into the most common life cycle stages can be of use in understanding, within each system, which life cycle stage is worth of further investigation and closer attention in order to minimize the overall GHG emissions.

Finally, this article has also confirmed that a full cradle-to-grave perspective must be adopted if LCA is to inform conclusions about environmental burdens. More specifically, had a cradle-to-gate perspective been adopted for the present, assessment results would have been the exact opposite of what they currently are. In this respect, findings from this research reinforce the plea for enhanced precision and a crystal-clear methodological approach in LCA such that shifts in environmental burdens from one life cycle stage to the other can be avoided.

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