International Journal of Construction Management

ISSN: 1562-3599 (Print) 2331-2327 (Online) Journal homepage: https://www.tandfonline.com/loi/tjcm20

Life cycle assessment of domestic hot water systems: a comparative analysis

Poorang Piroozfar, Francesco Pomponi & Eric R.P. Farr

To cite this article: Poorang Piroozfar, Francesco Pomponi & Eric R.P. Farr (2016) Life cycle assessment of domestic hot water systems: a comparative analysis, International Journal of Construction Management, 16:2, 109-125, DOI: 10.1080/15623599.2016.1146111

To link to this article: https://doi.org/10.1080/15623599.2016.1146111

Published online: 19 Apr 2016.

International Journal of Construction Management, 2016
Vol. 16, No. 2, 109−125, http://dx.doi.org/10.1080/15623599.2016.1146111

Life cycle assessment of domestic hot water systems: a comparative analysis

Poorang Piroozfar [a,b]*, Francesco Pomponi [a,†] and Eric R.P. Farr[c,‡]

[a]*School of Environment and Technology, University of Brighton, Cockcroft Building, Brighton, BN2 4GJ, East Sussex, UK;* [b]*@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;* [c]*New School of Architecture and Design, 1249 F Street, San Diego, CA 92101, USA*

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

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 the 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 on 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 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 an 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 environment-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

*Corresponding author. Email: a.e.piroozfar@brighton.ac.uk
†Present address: Department of Engineering, University of Cambridge, Trumpington Street, CB2 1PZ Cambridge, UK.
‡Present address: Founding Director of NONAMES Design Research Foundation, 1249 F Street, San Diego, CA 92101, USA.

'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.

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 contexts or in geographical settings, using different equipment configurations 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.

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 four 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 impact in production and manufacturing processes. This is due to a much higher impact of substituted electricity in the use phase, which exceeds the small differences in the other stages.

Solar domestic hot water systems (solar DHWSs)

An LCA of a solar thermal collector, where an overall primary energy consumption of 11.5 Giga Joule (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 a 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 (transport, 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 less 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 6.3−10 kg CO_2, acidification potential of 46.6−70 g SO_2, eutrophication of 2.1−3.1 g phosphate and photochemical oxidant of 0.99−1.5 g 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, an oil boiler and an electrical immersion heater. For these three systems they show that the SHWS would pay back 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 Gigawatthour GWh_{el} in 1978 to 1513 GWh_{el} (2.4%) in 2007. They also investigate scenarios for future development in the share of renewable solar energy in domestic hot water provision and speculate on 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 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 typical US 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 a 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 a year, and the life cycle cost payback varies 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 (seven SHWS configurations, four different fuels for the auxiliary systems and four base cases without SHWSs) to meet the daily heating energy for hot water demand of two dwellings and two 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 a final decision should be made based on a comparison between different benefits offered with regard 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 scope of the LCA in each study. Limitations of some studies, regardless of the

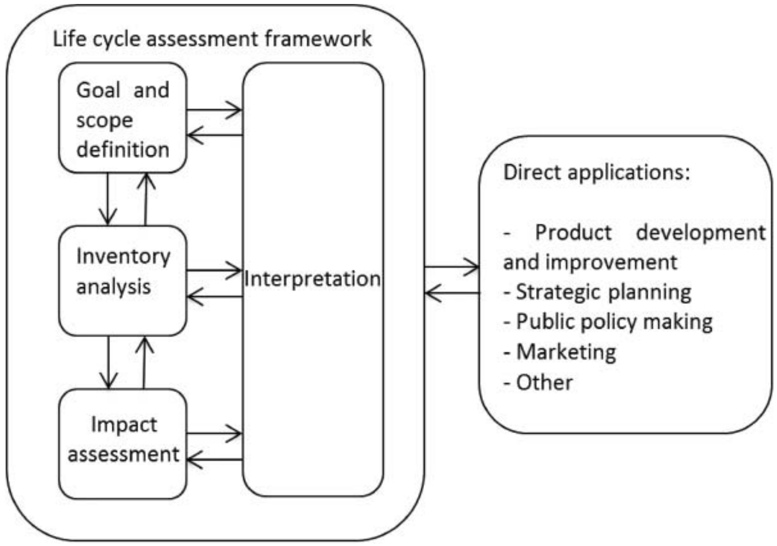

Figure 1. Life cycle methodological framework.
Source: ISO (2006a).

validity and reliability of their results, render them very case-specific, where no or very little further generalization can be made. Some, by contrast, try to take into account the generalization factor but do not 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 exception. Given these inevitable contextual boundaries, this research attempts to take all measures to ensure objective results are reached that are robust for validity and reliability tests.

Research methodology and design

This research uses a single-case study with a 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 the case of current research which is heavily reliant 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 the 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 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.

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 the depth and breadth of the assessment. The LCI phase involves the necessary data collection phase. Finally, during the LCIA phase, the significance of potential environmental impacts is quantified using the results from the LCI stage.

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).

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 here consists of 16 apartments and is supposed to be located in the city of Brighton and Hove, in 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.

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

- Its suitability for modern contemporary life style.
- Its clear spatial layout which makes the intended Mechanical & Eletrical (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 widely 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.

Functional unit, systems and system boundaries

The functional unit was defined as the production of 392,448,000 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 four showers a day (one shower/day/inhabitant and four 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.

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.

Electric shower

The 7500W Triton Seville (Figure 3a) 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).

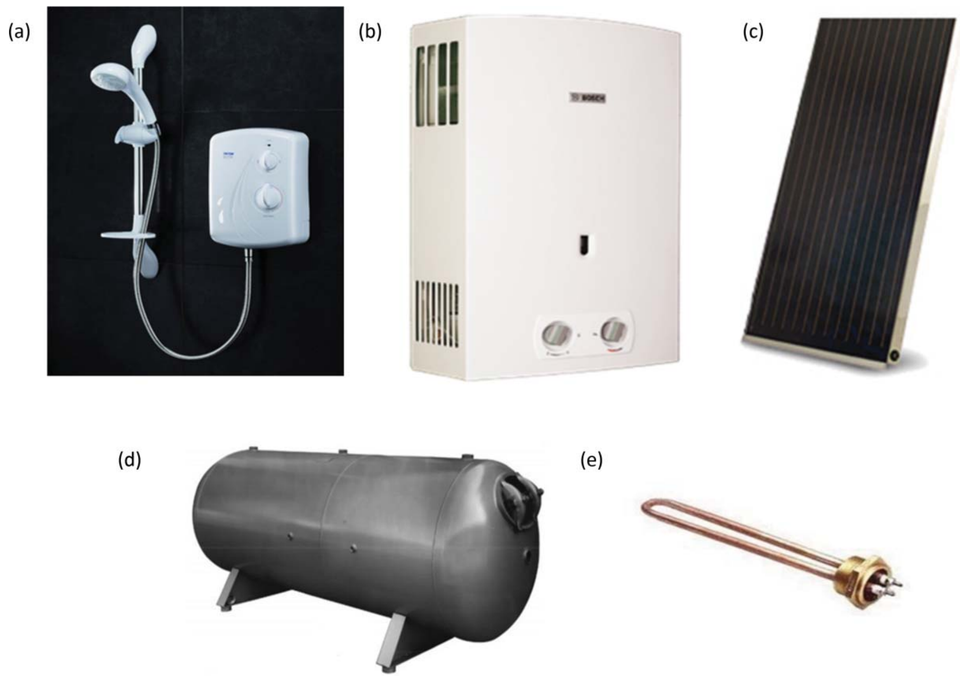

Figure 3. Pictures of some components of the systems assessed. <<t/s: please add opening brackets before a), b) etc.>>

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 the quality of the raw material, which results in waste.

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

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:

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

Considering an efficiency of 80%, the demand is:

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

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. The 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.

Passage heater with gas

With a water flow of 12 l/min, the Bosch Comfort Line GWH 250 B ND (Figure 3b) was selected as a nominal product for the 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 used 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 $1.426 \times 280 = 400$tkm.

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%

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

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

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

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

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 refinery	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%

Solar heater with electric backup

A conventional thermosyphon was selected for the 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 at an average of 280km distance, giving $2\times280 = 560$tkm as a result.

For the use phase the online Valentin Software was used (ValentinSoftware 2014). For Brighton, 20m^2 of collectors with a 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 need 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:

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

Considering an efficiency of 80%, the demand is:

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

Table 3 shows the solar heater inventory.

Electric boiler

The same auxiliary system as explained in the above option was selected for this option too – that is, a thermal reservoir with a 1000-litre 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 is 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 at an average of 255km distance, which will result in $1.568\times255 = 400$tkm.

Assuming that the boiler works for four 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:

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

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

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

Table 4 shows the electric boiler inventory.

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 2m^3/h. So, under the assumption that the boiler works for four hours a day, multiplying the number of use hours by its consumption, the energy demand for the use phase of the product can be

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%

calculated:

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

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

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

Table 5 shows the gas 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
Electricity	Electricity, low voltage, at grid/GB	182500
Disposal scenario		
Type	SimaPro	Allocation
England	Waste scenario/Eng	100%

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 of the 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 the most 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.

This specific detail of the results can be 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.

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%

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

	Assessed DHW systems									
	Electric shower		Passage heater with gas		Solar heater with electric backup		Electric boiler		Gas boiler	
Life cycle stages	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%

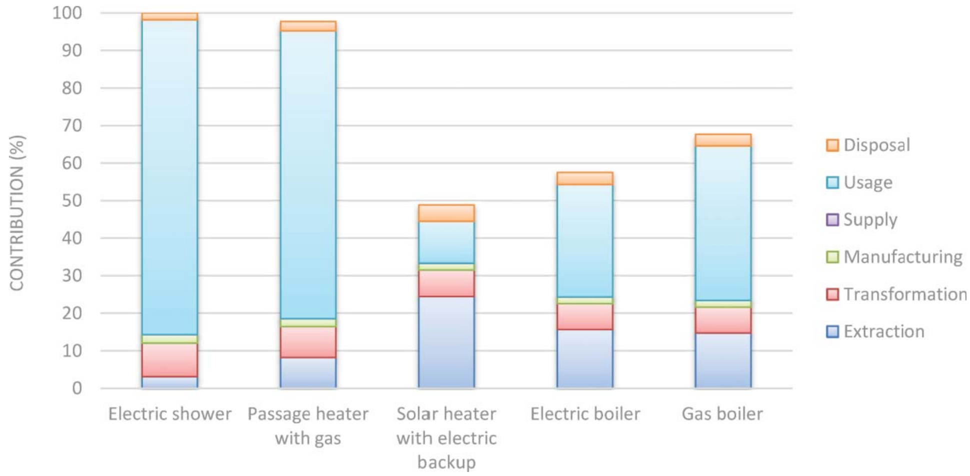

Figure 4. Normalized percentage values of the impacts of different life cycle phases for the DHW systems considered.

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

To contextualize the findings from this research among other published studies, it is worth noting that Tsilingiridis et al. (2004) report the solar heater as the best option, followed by gas and then electric devices, whereas Taborianski and Prado (2004) indicate the electric shower as the system with the most impact, 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 worth noting that such results depend heavily on the perspective used, which in this article is – once again – a cradle-to-grave. Indeed, had a cradle-to-gate perspective been adopted, 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 at 73% of the solar system, then the gas boiler at 70%, the passage heater with gas at 56% and the electric shower at 43%. If the DHW systems assessed were ranked from first to fifth, the cradle-to-gate ranking would be the exact opposite of that from the cradle-to-grave study (Table 7).

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, although the final results do seem to be context-dependent, as discussed above with respect to Tsilingiridis et al. (2004) and Taborianski and Prado (2004).

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

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 of operation and maintenance and of 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 the most damaging alternative being chosen 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 after just 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 vary greatly from one study to another, 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).

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, the results indicate the solar heater with electric backup as a better option than all the others – 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 in the other four options, the solar heater uses solar irradiation to heat the water – very clean and renewable source of energy for providing domestic hot water. However, the findings of this research do not necessarily mean that a solar heater is always the best option. Firstly, it was analysed as a particular installation 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, the 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 the use phase. However, this represents a topic that deserves research on its own right through, for instance, life cycle costing.

Although maximum care has been taken to ensure that a robust and valid study 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 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 study, 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.

Acknowledgements

The authors wish to thank Mr Marcel Vechi, MSc. who was instrumental in the data generation and helped with data analysis for this research under the Brazilian Science without Borders Programme at the School of Environment and Technology, University of Brighton, UK, during summer 2014. Special thanks also go to the editor-in-chief, associate editor(s), guest editor(s) and reviewers of the *International Journal of Construction Management* special issue on sustainable construction, whose constructive comments helped further improve the quality of this paper.

Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed at here.

ORCID

Poorang Piroozfar http://orcid.org/0000-0001-9765-8148

Francesco Pomponi http://orcid.org/0000-0003-3132-2523

References

Allen SR, Hammond GP, Harajli HA, McManus MC, Winnett AB. 2010. Integrated appraisal of a solar hot water system. Energy. 35:1351−1362. doi: http://dx.doi.org/10.1016/j.energy.2009.11.018

Altoé L, Oliveira Filho D, Carlo JC. 2012. Análise energética de sistemas solares térmicos para diferentes demandas de água em uma residência unifamiliar [Energy analysis of different solar thermal systems for water demand in a single-residency dwelling]. Ambiente Construído. 12:75−87.

Ardente F, Beccali G, Cellura M, Lo Brano V. 2005a. Life cycle assessment of a solar thermal collector. Renew Energy. 30:1031−1054. doi: http://dx.doi.org/10.1016/j.renene.2004.09.009

Ardente F, Beccali G, Cellura M, Lo Brano V. 2005b. Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances. Renewable Energy. 30:109−130. doi: http://dx.doi.org/10.1016/j.renene.2004.05.006

Bryar MR. 2000. An examination of case study research. Nurse Res. 7:61−78.

Crawford RH, Treloar GJ. 2004. Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia. Solar Energy. 76:159−163. doi: http://dx.doi.org/10.1016/j.solener.2003.07.030

Crawford RH, Treloar GJ, Ilozor BD, Love PED. 2003. Comparative greenhouse emissions analysis of domestic solar hot water systems. Build Res Info. 31:34−47. doi: 10.1080/09613210210160800

EIA (Energy Information Administration). 2013. Heating and cooling no longer majority of U.S. home energy use [Internet]. US Energy Information Administration; [cited Aug 2014]. Available from: http://www.eia.gov/todayinenergy/detail.cfm?id=10271

Greening B, Azapagic A. 2014. Domestic solar thermal water heating: a sustainable option for the UK? Renew Energy. 63:23−36. doi: http://dx.doi.org/10.1016/j.renene.2013.07.048

Hang Y, Qu M, Zhao F. 2012. Economic and environmental life cycle analysis of solar hot water systems in the United States. Energy Build. 45:181−188. doi: http://dx.doi.org/10.1016/j.enbuild.2011.10.057

Hernandez P, Kenny P. 2012. Net energy analysis of domestic solar water heating installations in operation. Renew Sustain Energy Rev. 16:170−177. doi: http://dx.doi.org/10.1016/j.rser.2011.07.144

Ip K, Miller A. 2012. Life cycle greenhouse gas emissions of hemp−lime wall constructions in the UK. Resources Conserv Recycling. 69:1−9. doi: http://dx.doi.org/10.1016/j.resconrec.2012.09.001

IPCC (Intergovernmental Panel on Climate Change). 2013.. Working group I contribution to the fifth assessment report of the Intergovernmental Panel on Climate Change. Climate change 2013 − the physical science basis. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM, editors. , Cambridge: Cambridge University Press.

ISO. 2006a. BSI EN ISO 14040:2006 Environmental management − life cycle assessment − principles and framwork. London: British Standard Institution.

ISO. 2006b. BSI EN ISO 14044:2006 Environmental management − life cycle assessment − requirement and guidelines. London: British Standard Institution.

Kalogirou S. 2009. Thermal performance, economic and environmental life cycle analysis of thermosiphon solar water heaters. Solar Energy. 83:39−48. doi: http://dx.doi.org/10.1016/j.solener.2008.06.005

Koroneos CJ, Nanaki EA. 2012. Life cycle environmental impact assessment of a solar water heater. J Clean Prod. 37:154−161.

Martinopoulos G, Tsilingiridis G, Kyriakis N. 2013. Identification of the environmental impact from the use of different materials in domestic solar hot water systems. Applied Energy. 102:545−555.

Masruroh NA, Li B, Klemeš J. 2006. Life cycle analysis of a solar thermal system with thermochemical storage process. Renew Energy. 31:537−548. doi: http://dx.doi.org/10.1016/j.renene.2005.03.008

MBI (Modular Building Institute). 2009. Commercial modular construction report. Charlottesville, VA: Modular Building Institute (MBI).

Newman I, Ridenour C. 2008. Mixed methods research: exploring the interactive continuum. Carbondale: Southern Illinois University Press.

Stake RE. 1995. The art of case study research. Thousand Oaks (CA): Sage.

Taborianski VM. 2002. Avaliação da contribuição das tipologias de aquecimento de água residencial para a variação do estoque de gases de efeito estufa na atmosfera [Evaluation of contribution of residential water heating systems to the variation of the stock of greenhouse gases in the atmosphere]. São Paulo: Escola Politécnica da Universidade de São Paulo Catarina – USP.
Taborianski VM, Prado RTA. 2004. Comparative evaluation of the contribution of residential water heating systems to the variation of greenhouse gases stock in the atmosphere. Build Environ. 39:645–652.
Thirugnanasambandam M, Iniyan S, Goic R. 2010. A review of solar thermal technologies. Renew Sust Energy Rev. 14:312–322.
Tsang EWK. 2014. Case studies and generalization in information systems research: a critical realist perspective. J Strat Info Syst. 23:174–186. doi: http://dx.doi.org/10.1016/j.jsis.2013.09.002
Tsilingiridis G, Martinopoulos G. 2010. Thirty years of domestic solar hot water systems use in Greece – energy and environmental benefits – future perspectives. Renew Energy, 35:490–497. doi: http://dx.doi.org/10.1016/j.renene.2009.05.001
Tsilingiridis G, Martinopoulos G, Kyriakis N. 2004. Life cycle environmental impact of a thermosyphonic domestic solar hot water system in comparison with electrical and gas water heating. Renew Energy. 29:1277–1288.
Unilever. 2011. UK sustainable shower study [Internet]; [accessed July 2015]. Available from: http://www.unilever.co.uk/media-centre/pressreleases/2011/sustainableshowerstudy.aspx
ValentinSoftware. 2014. [Cited June 2015]. Available from: http://www.valentin-software.com/en/downloads/products
Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, … Wernet G. 2013. Overview and methodology. Data quality guideline for the ecoinvent database Version 3. ecoinvent Report 1(v3). St. Gallen: The ecoinvent centre – Swiss Centre for Life Cycle Inventories.
Yin RK. 2009. Case study research: design and methods. 4th ed. Thousand Oaks (CA): Sage Publications.
Zambrana-Vasquez D, Aranda-Usón A, Zabalza-Bribián I, Jañez A, Llera-Sastresa E, Hernandez P, Arrizabalaga E. 2015. Environmental assessment of domestic solar hot water systems: a case study in residential and hotel buildings. J Clean Prod. 88:29–42.