



Domestic solar thermal water heating: A sustainable option for the UK?[☆]



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ABSTRACT

This paper considers life cycle environmental sustainability of solar water heating systems in regions with low solar irradiation, such as the UK. The results suggest that flat plate collectors have slightly lower environmental impacts than evacuated tube designs. Reducing the current energy losses of 65%–45% would reduce the impacts by around 35%. Compared to a gas boiler, solar thermal systems are a better option for only five out of 11 environmental impacts considered, with global warming and depletion of fossil resources being lower by 88% and 83%, respectively. Other impacts such as human and eco-toxicity are up to 85% higher. The solar systems score better relative to electrical water heating for eight out of 11 impacts. They are also environmentally more sustainable than heat pumps for seven categories. However, their potential is hampered because they need a back-up heating system, typically gas boiler. For this reason as well as due to a lack of suitable locations and poor efficiency, the potential of solar thermal systems to contribute to a more sustainable domestic energy supply in the UK is limited.

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1. Introduction

The domestic sector in the UK currently accounts for one third of national energy consumption and one quarter of UK greenhouse gas emissions [1,2]. This is due to the heavy reliance on fossil fuels of domestic activities such as space and water heating [3]. The majority (84%) of water heating in the UK is provided by natural gas with the rest supplied by electricity [3]. The Government has identified micro-generation as a key option for reducing greenhouse gas (GHG) emissions from the domestic sector and for contributing towards UK's GHG reduction targets of 34% by 2020 and 80% by 2050 [4,5]. In the UK, micro-generation is defined as the generation of electricity of up to 50 kW and/or heat of up to 45 kW from a low-carbon source [5]. Since 2003, policy, legislation and incentives related to micro-generation have been introduced to improve public awareness and encourage uptake. This has included the Micro-generation Strategy [6,7] and incentives such as the Feed-in-Tariff (FiT) and Renewable Heat Incentive (RHI) [8,9].

Solar thermal micro-generation systems could help reduce UK GHG emissions arising from water heating in the domestic sector [10,11]. Solar thermal is one of the most established micro-generation technologies in the UK with more than 100,000 units installed to date [11]. However, this is still significantly lower compared to other countries such as Germany which has over 1 million units in operation [12]. The RHI scheme is expected to increase the number of solar thermal installations as it will offer payments of 17.3 pence per kWh of renewable heat generated [13].

Several studies have considered the life cycle environmental sustainability of solar thermal systems using life cycle assessment (LCA). However, most of these have been carried out for countries where annual solar irradiation is much more suitable for the application of solar thermal than in the UK, including Southern Europe and the USA [14–24]. As far as the authors are aware, there is only one other study of solar thermal systems for the UK [25] but, like some other studies [15–17,22], it has not considered the operation, maintenance and decommissioning stages.

Furthermore, most LCA studies have only considered GHG emissions and embodied energy as indicators of environmental performance, with no estimation of other environmental impacts [14,19,21,22,25]. Others have only estimated the energy used in the life cycle of solar thermal systems [18,20]. Only a limited number of studies have gone further by estimating other environmental impacts such as acidification, ozone layer depletion, resource use and/or biodiversity [15–17,23,24]. However, with the exception of

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one study [23], these studies have not considered the full life cycle of solar thermal systems.

Despite there being two main types of solar thermal system – evacuated tube collectors and flat plate collectors [26] – most studies focus on the latter and only two have considered both types [14,21]. Therefore, the environmental impacts of evacuated tube collectors are less well known. Moreover, most studies compare solar thermal systems with conventional heat sources such as gas boilers and electrical water heating [14,16,17,19,21,23,25] so that, as far as we are aware, there are no comparative studies with alternative micro-generation systems.

This paper sets out to evaluate the life cycle environmental sustainability of solar thermal systems for the UK conditions and to find out what potential they may have in contributing to a more sustainable energy supply in the domestic sector. For these purposes, first the individual solar thermal systems are compared to their current fossil fuel alternatives such as water heating by natural gas and electricity as well as to heat pumps, an increasingly popular alternative micro-generation system. This is followed by an evaluation of the environmental sustainability of the solar thermal systems at the UK level, assuming a projected future mass deployment of these technologies. The potential of the solar thermal to contribute to UK climate change targets is also investigated. Both flat plate and evacuated tube collectors are considered.

2. Methodology

Life cycle assessment has been used as a tool for evaluating the life cycle environmental sustainability of solar thermal systems and their alternatives. The LCA methodology used in this study follows the ISO 14040 and 14044 guidelines [27,28]. The LCA software GaBi v.4.4 [29] has been used to model the systems and the CML 2 Baseline 2001 methodology [30] has been applied to estimate the environmental impacts. The following sections describe the goal of the study, system boundaries, the assumptions and data.

2.1. Goal and scope definition

The goal of this study is to estimate the life cycle environmental impacts of flat plate and evacuated tube solar thermal systems for water heating in the domestic sector in the UK and compare them to water heating provided by alternative means: a natural gas condensing boiler, electricity and heat pumps. The former two options are chosen as the currently most-widely used means for domestic water heating and the latter as the emerging option that could replace the conventional water heating systems.

The functional unit is defined as the generation of 1 kWh of thermal energy for water heating. As shown in Fig. 1, the scope of the study is from ‘cradle to grave’ encompassing manufacture, operation, installation and decommissioning of solar thermal systems. Further detail on the system boundaries can be found in Table 1. The design capacity of the system is 2.8 kW and the assumed lifetime is 25 years.

2.2. System description, data and assumptions

2.2.1. Solar thermal systems

Solar thermal systems are used to produce hot water in dwellings by the absorption of solar irradiation [31]. Solar energy is captured by a collector and converted to heat via a heat-transfer fluid, typically propylene glycol. The fluid, circulated around the system by an electric pump (in the ‘active system’; ‘passive systems’ do not require a pump), transfers the heat to a storage cylinder where it is used to produce hot water. A back-up heat source (e.g. electric immersion heater or a gas boiler) is generally required in

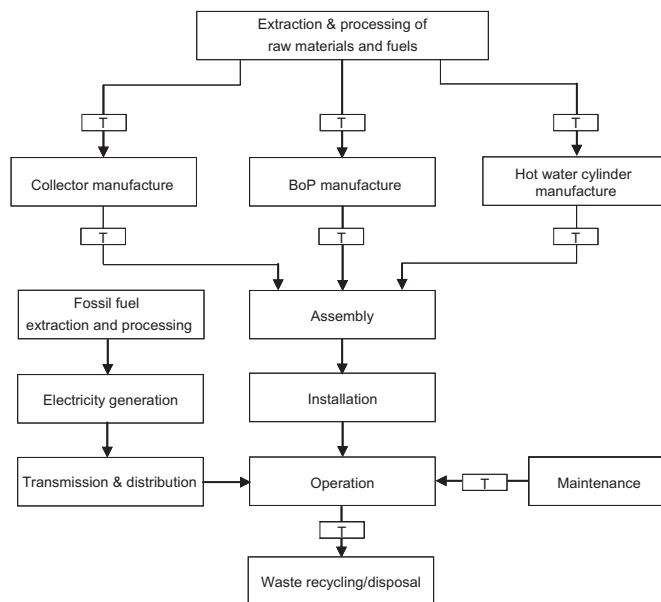


Fig. 1. The life cycle of solar thermal systems. (BoP – Balance of Plant; T – transport).

the UK to ensure that water is heated to a suitable temperature when solar irradiation is insufficient [31].

Two main types of collector are used for solar thermal systems: flat plate (FPCs) and evacuated tube collectors (ETCs) [26]. The former typically use as the absorber a metal plate (e.g. copper or aluminium) coated with a black chrome layer [32]. Tubes containing the heat-transfer fluid are attached to the underside of the collector. The absorber assembly is encased within a glazed box made from solar glass to reduce heat loss from the collector [33]. ETCs use finned heat pipes (typically made from copper) inside vacuum-sealed glass tubes [32]. The fins are coated with a selective coating (e.g. black chrome which is more efficient in absorbing heat than ordinary black paint) and the pipes contain a liquid (e.g. methanol) which undergoes an evaporating–condensing cycle as it is heated and cooled [33]. The heat pipes are connected to a manifold which facilitates heat exchange from the liquid to a heat-transfer fluid flowing through the manifold.

The performance of solar thermal systems is most commonly described using ‘solar fraction’. This is the percentage of hot water demand supplied by the system relative to the total demand. Owing to their higher levels of insulation and lower heat losses, ETCs are more efficient per square metre than equivalent FPCs [26]. However, this does not translate into a greater energy output because

Table 1
System boundaries for solar thermal systems.

System boundaries	Solar thermal systems
Included within system boundaries	<ul style="list-style-type: none"> Extraction and processing of fuels and raw materials System manufacture: collector, framework, pipework, pump, expansion vessel, hot water cylinder and assembly Installation: transport of engineer to site Operation: electricity for circulating the heat-transfer fluid through the system Maintenance (replacement of propylene glycol) Decommissioning: metals and glass recycling, inert material landfill disposal, wastewater treatment of propylene glycol; incineration of methanol All transport
Excluded from system boundaries	<ul style="list-style-type: none"> Energy input into installation

the geometry of FPCs generally results in a larger absorber area (up to five times). For example, a field trial by the Energy Saving Trust (EST) of 54 FPC and 34 ETC systems found that they generate on average a similar amount of heat: 1156 and 1140 kWh, respectively [26]. Therefore, we assume in this study the energy output of both collectors to be identical.

In the UK global solar irradiation on a horizontal surface can vary from around 800 kWh/m² per year in the very North of Scotland to above 1200 kWh/m² per year in the South-West of

England [34]. In this study we have taken solar irradiation to be the mean value of these two extremes (1000 kWh/m² per year). Collectors with an area of 4 m² are considered as this size is recommended by manufacturers for the average family home [35,36]. It is assumed that the systems are roof-mounted, with no shading, at an optimum inclination of 30° [37] which increases the incoming solar irradiation by 10% compared to no inclination [25]. Therefore, the solar resource available to a collector with the above characteristics is 4400 kWh/yr (1000 kWh/m² yr × 4 m² × 1.1).

Table 2

Specification summary for the solar thermal systems.

Component, system or life cycle stage	Flat plate collector	Evacuated tube collector
Absorber (per m ² gross area)	<ul style="list-style-type: none"> • Anti-reflex coating: 1 m² • Copper: 2.82 kg • Low-alloyed steel: 32 kg • Low-iron solar glass: 9.12 kg • Sheet rolling: 2.82 kg • Selective coating (black chrome) copper sheet: 1 m² 	<ul style="list-style-type: none"> • Anti-reflex coating: 1 m² • Copper: 2.8 kg • Low-alloyed steel: 20 kg • Glass tube, borosilicate: 14.2 kg • Sheet rolling: 2.8 kg • Selective coating (black chrome) copper sheet: 1 m² • Hydrochloric acid (30% in water): 0.113 kg • Organic chemicals (methanol): 0.0113 kg
Framework (per m ² gross area)	<ul style="list-style-type: none"> • Aluminium: 3.93 kg • Rock wool: 2.43 kg • Stainless steel: 4.14 kg 	<ul style="list-style-type: none"> • Stainless steel: 4 kg • Rock wool: 2.03 kg
Heat-transfer fluid (per m ² gross area)	<ul style="list-style-type: none"> • Propylene glycol: 1.01 kg 	<ul style="list-style-type: none"> • Propylene glycol: 0.65 kg
Balance of plant (i.e. pipework, manifold, insulation)	<ul style="list-style-type: none"> • Pipework and manifold: copper: 8 kg • Pipework insulation: elastomere: 4 kg 	<ul style="list-style-type: none"> • Pipework and manifold: copper: 8 kg • Pipework insulation: elastomere: 4 kg
Miscellaneous (per m ² gross area)	<ul style="list-style-type: none"> • Corrugated board: 3.68 kg • Brazing solder (cadmium free): 0.00368 kg • Silicone product: 0.0588 kg • Soft solder: 0.0588 kg • Synthetic rubber: 0.732 kg • Water: 9.4 kg • Water, completely softened: 1.38 kg 	<ul style="list-style-type: none"> • Corrugated board: 3.33 kg • Brazing solder (cadmium free): 0.10 kg • Silicone product: 0.0533 kg • Soft solder: 0.0588 kg • Synthetic rubber: 0.667 kg • Water: 53.6 kg • Water, completely softened: 0.90 kg
Manufacturing energy	<ul style="list-style-type: none"> • Electricity (medium voltage): 4.18 MJ 	<ul style="list-style-type: none"> • Electricity (medium voltage): 61.2 MJ • Natural gas: 16.5 MJ
Pump	<ul style="list-style-type: none"> • Aluminium: 0.05 kg • Cast iron: 3 kg • Copper: 0.625 kg • Polyvinylchloride: 0.075 kg • Stainless steel: 2.3 kg • Synthetic rubber: 0.0175 kg 	<ul style="list-style-type: none"> • Aluminium: 0.05 kg • Cast iron: 3 kg • Copper: 0.625 kg • Polyvinylchloride: 0.075 kg • Stainless steel: 2.3 kg • Synthetic rubber: 0.0175 kg
Expansion vessel	<ul style="list-style-type: none"> • Alkyd paint: 0.07 kg • Butyl acrylate: 0.7 kg • Corrugated board: 0.5 kg • Low-alloyed steel: 4.7 kg • Polypropylene: 0.025 kg • Welding: 0.5 m • Electricity (medium voltage): 30.996 MJ • Light fuel oil: 20 MJ 	<ul style="list-style-type: none"> • Alkyd paint: 0.07 kg • Butyl acrylate: 0.7 kg • Corrugated board: 0.5 kg • Low-alloyed steel: 4.7 kg • Polypropylene: 0.025 kg • Welding: 0.5 m • Electricity (medium voltage): 30.996 MJ • Light fuel oil: 20 MJ
Hot water cylinder	<ul style="list-style-type: none"> • Alkyd paint: 0.42 kg • Glass wool: 8.34 kg • Low-alloyed steel: 91.74 kg • Polyvinylchloride: 0.83 kg • Stainless steel: 16.68 kg • Tap water: 257.29 kg • Welding: 3.22 m • Electricity (medium voltage): 52.09 MJ • Natural gas: 63.80 MJ 	<ul style="list-style-type: none"> • Alkyd paint: 0.42 kg • Glass wool: 8.34 kg • Low-alloyed steel: 91.74 kg • Polyvinylchloride: 0.83 kg • Stainless steel: 16.68 kg • Tap water: 257.29 kg • Welding: 3.22 m • Electricity (medium voltage): 52.09 MJ • Natural gas: 63.80 MJ
Operation	<ul style="list-style-type: none"> • Electricity: 55 kWh/year 	<ul style="list-style-type: none"> • Electricity: 55 kWh/year
Maintenance	<ul style="list-style-type: none"> • Propylene glycol: 13.1 kg/25 years (heat-transfer fluid topped up every 5 years) 	<ul style="list-style-type: none"> • Propylene glycol: 15.77 kg/25 years (heat-transfer fluid topped up every 5 years)
Decommissioning	<ul style="list-style-type: none"> • Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Steel: 61.7% recycled; 38.3% landfilled • Plastics: 100% landfilled • Propylene glycol: 100% to wastewater treatment 	<ul style="list-style-type: none"> • Aluminium: 90% recycled; 10% landfilled • Copper: 41% recycled; 59% landfilled • Steel: 61.7% recycled; 38.3% landfilled • Plastics: 100% landfilled • Propylene glycol: 100% to wastewater treatment • Glass: 62% recycled; 38% landfilled • Methanol: 100% to hazardous waste incineration

The efficiency of solar thermal systems in the UK typically ranges from 30 to 40% due to the energy losses from the systems [26,37,38]. Thus, in this study, the efficiency of both systems is assumed to be 35%. The majority of the incident radiation (around 40%) is lost via the glazing, reflection, conduction, convection and re-emittance [37]. Smaller losses occur from the pump and collector pipework (~10%) and from storage and distribution (~15%) [25].

Based on the solar resource available and the assumed energy losses, both systems are assumed to produce 1540 kWh/yr (385 kWh/m² yr). Given that the average hot water demand of UK households is 3216 kWh/yr [3], this corresponds to a solar fraction of 48%.

The system specification and the data for the solar thermal systems are summarised in Table 2. Data for the operation of the system have been obtained from manufacturers and field trials [26,31,35,36] and data for the manufacture, installation and maintenance are sourced from the Ecoinvent database [39,40]. All data reflect UK conditions with the datasets adapted for the UK energy mixes, transport distances and the current waste management practices for different materials [39,41,42]. The following provides more detail on the FPCs and ETCs and the other parts of the system.

2.2.1.1. FPC. A copper absorber with a black chrome selective coating is assumed. Copper is used for the pipework attached to the underside of the absorber. The header pipe (manifold) is also made from copper. Propylene glycol is assumed for the heat-transfer fluid. The absorber is enclosed within low-iron content solar glass, which is coated with an anti-reflexive coating to reduce the amount of solar irradiation reflected away from the collector. Aluminium and stainless steel are the main materials used for the framework and back plate. Mineral wool is used for thermal insulation.

2.2.1.2. ETC. The evacuated tube collector uses a series of borosilicate glass tubes with each containing a copper finned heat pipe, also coated with a black chrome selective coating. An anti-reflexive coating is applied to the glass tubes. Methanol is assumed for the liquid which undergoes an evaporating–condensing cycle and propylene glycol is assumed for the heat-transfer fluid flowing through the manifold. The heat pipes are connected to a copper manifold. The framework of the collector is made from stainless steel and rock wool is used for insulation.

2.2.1.3. Expansion vessel and pump. A 25 L expansion vessel is assumed for both solar thermal systems. The vessel is made predominantly from low-alloyed steel and is coated with alkyl paint. A 100 W electric pump is assumed in each system to circulate the heat-transfer fluid around the full length of the pipework [39]. Based on findings by the EST, the pump is assumed to consume 55 kWh of electricity per annum [37]. Cast iron and stainless steel are the main materials assumed to be used for the pump.

2.2.1.4. Hot water cylinder. For both solar collector systems a 250 L hot water cylinder is used for heat storage and supply based on manufacturers' assumptions that each occupant uses around 60 L of hot water per day [35]. The cylinder is made predominantly from steel and glass fibreglass. Glass wool is used for insulation.

2.2.1.5. Decommissioning. After 25 years of service life, the systems are dismantled. It is assumed that metal and glass components are recycled at the current UK recycling rates (Table 2); the system has been credited for the recycled materials. Plastic materials are assumed to be landfilled. The heat-transfer fluid (propylene glycol) from the collectors is treated in a wastewater treatment plant and methanol is incinerated.

Table 3
Summary of transport modes and distances for solar thermal systems.

Transport stage	Mode of transport	Distance (km)
Solar thermal system manufacture (raw materials transport)	Freight train	200
	Lorry: >16 tonne	100
Solar thermal system Installation	Lorry > 16 tonne	200
	Van < 3.5 tonne (equipment to site)	200
Maintenance	Van < 3.5 tonne	200
	(equipment to site)	

2.2.1.6. Transport. Generic transport distances of 100 km by lorry and 200 km by rail have been assumed for the transport of raw materials. A distance of 200 km by van has been used for the transport of the solar thermal systems to the installation site (see Table 3).

2.2.2. Alternative options for water heating

Table 4 outlines the main characteristics of the alternative options for providing domestic hot water considered in this paper: condensing gas boiler and air-, water- and ground-source heat pumps. The system boundary for all the alternatives is from cradle to grave, including manufacture, operation and decommissioning. For a detailed description of these options and the LCA data used, see Greening and Azapagic [43]. The life cycle of electrical heating is also from 'cradle to grave', including the same hot water cylinder assumed in all the other systems. The UK electricity mix has been assumed and the LCA data are from Ecoinvent [39].

3. Results and discussion

3.1. Environmental impacts of solar thermal systems

The life cycle environmental impacts for the two solar thermal systems are given in Fig. 2. The results indicate that the FPC system has on average 7% lower impacts than ETC for seven of the 11 categories considered, ranging from 1% lower acidification to 11% lower global warming and ozone layer depletion potentials. This is due to the energy-intensive manufacture of the ETC system, which is equal to 77.7 MJ/m² compared to 4.18 MJ/m² for the FPC. The production of the glass tubes is the major contributor to this high energy consumption. The ETC is a better option for the freshwater, marine, terrestrial and human toxicity potentials; however, the average difference is only 1.4% because the ETC system requires marginally less copper and steel and uses no aluminium for the framework.

As indicated in Figs. 3 and 4, the manufacture contributes the majority (on average 60%) to the impacts for both systems. The operation of the systems is the next largest contributor (~20%) due to the use of electricity for the pumps which circulate the heat-transfer fluid. Maintenance of the two systems adds on average 12% of the total impacts due to the replacement of the heat-transfer fluid. Installation, disposal and transport contribute around 6%, 2.6% and 0.3%, respectively. However, disposal has a higher contribution (~22%) to the eutrophication potential owing to the wastewater treatment of the heat-transfer fluid.

Table 4
Assumed efficiencies of alternative options for domestic water heating.

Technology	Capacity (kW)	Thermal efficiency or CoP ^a
Gas boiler (condensing)	10	90%
ASHP ^b	10	2.8 ^a
GSHP ^b	10	3.9 ^a
WSHP ^b	10	3.9 ^a

^a Coefficient of performance.

^b Heat pumps assumed to produce both space and water heating.

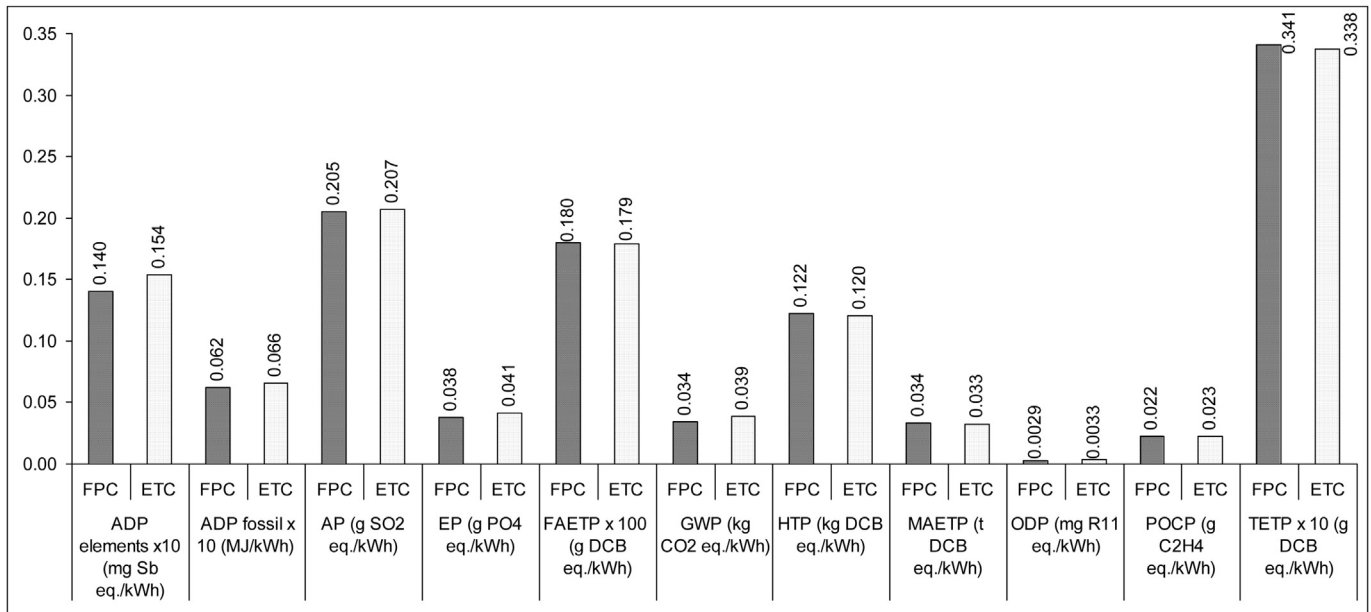


Fig. 2. Life cycle environmental impacts of the solar thermal systems. [FPC: Flat plate collector; ETC: Evacuated tube collector. Impact categories: ADP elements: Abiotic resource depletion of elements; ADP fossil: Abiotic resource depletion of fossil fuels; AP: Acidification potential; EP: Eutrophication potential; FAETP: Fresh water aquatic eco-toxicity potential; GWP: Global warming potential; HTP: Human toxicity potential; MAETP: Marine aquatic eco-toxicity potential; ODP: Ozone layer depletion potential; POCP: Photochemical ozone creation potential; TETP: Terrestrial eco-toxicity potential.]

The following section gives a brief overview of the findings for each impact; the discussion refers to the results shown in Figs. 2–4.

3.1.1. Abiotic resource depletion (ADP elements and fossil)

The FPC and ETC systems deplete 1.4 and 1.54 mg Sb eq./kWh of abiotic elements, respectively. This is mainly due to the use of copper and molybdenum for the production of the copper and steel components used in the system. The depletion of fossil fuels of 620–640 kJ/kWh, on the other hand, is predominantly (40–45%) due to the electricity used in the operation stage to pump the heat-transfer fluid and the manufacturing (35–40%) of the systems.

3.1.2. Acidification potential (AP)

Over a half of this impact, estimated at around 0.2 g SO₂ eq./kWh, is due to the system manufacture and in particular due to the emissions of SO₂ and NO_x from the generation of energy used for copper production.

3.1.3. Eutrophication potential (EP)

The EP ranges from 38 mg PO₄ eq./kWh for the FPC to 41 mg PO₄ eq./kWh for the ETC. The manufacture of the solar thermal systems is the main contributor (35%) due to NO_x emissions from the generation of electricity used in the production of steel. NO_x emissions associated with the electricity used to run the pump in the operation stage contribute a further 14% to the total EP. The high biochemical oxygen demand (BOD) from the life cycle of propylene glycol is the main contributor to EP for the maintenance and decommissioning stages.

3.1.4. Fresh water aquatic eco-toxicity (FAETP)

The values for FAETP for the FPC and ETC systems are similar: 18.0 and 17.9 g DCB eq./kWh, respectively. The major source of this impact is the manufacturing stage (around 94%) due to heavy metal emissions to fresh water of nickel, and to a lesser extent cobalt, during the production of stainless steel.

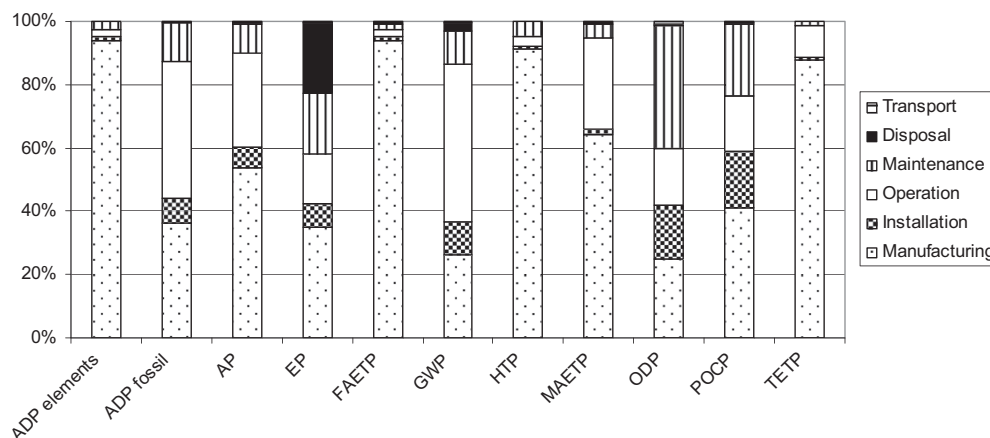


Fig. 3. Contribution analysis for the flat plate collector system. [For impacts nomenclature, see Fig. 2.]

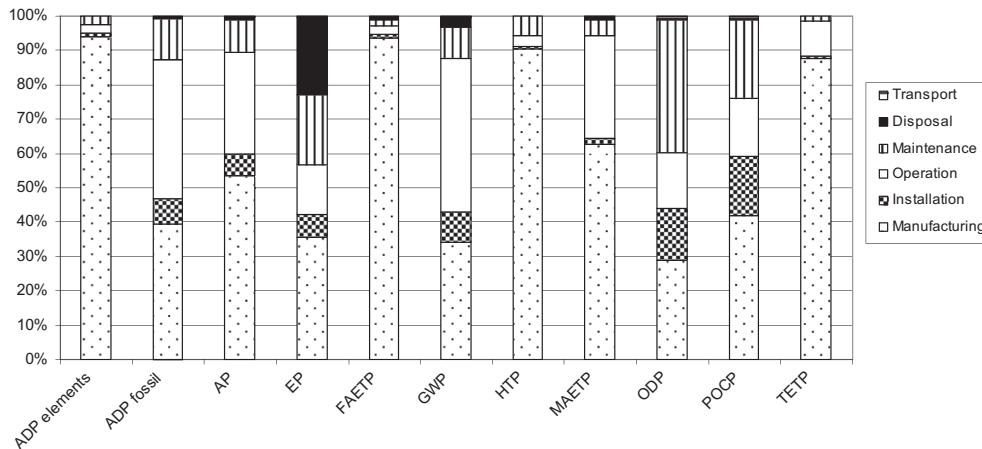


Fig. 4. Contribution analysis for the evacuated tube collector system. [For impacts nomenclature, see Fig. 2.]

3.1.5. Global warming potential (GWP)

GWP is estimated at 34 g for FPC and 39 g CO₂ eq./kWh for ETC. The operation stage is the main contributor (around 45–50%) due to the use of electricity for the pump. System manufacture contributes another 30%.

3.1.6. Human toxicity potential (HTP)

The heavy metal emissions of chromium and arsenic during the production of steel and copper contribute the majority (90%) of this impact, which is similar for both systems (~0.12 kg DCB eq./kWh).

3.1.7. Marine aquatic eco-toxicity potential (MAETP)

This impact is slightly lower for FPC than for ETC: 34 compared to 33 kg DCB eq./kWh, respectively. Hydrogen fluoride from both the life cycle of electricity used to run the pump and the production of the copper, aluminium and stainless steel required for the system is the major contributor (>95%).

3.1.8. Ozone depletion potential (ODP)

The value for ODP is low for both systems, ranging from 2.9 µg for FPC to 3.3 µg R11 eq./kWh for ETC. The major contributors are the emissions of halon 1211 (bromochlorodifluoromethane) and carbon tetrachloride arising mainly from the life cycles of the electricity and propylene glycol.

3.1.9. Photochemical ozone creation potential (POCP)

Both systems have a similar POCP (0.022–0.023 g C₂H₄ eq./kWh). The emissions of SO₂, CO, NO_x and non-methane VOCs from steel and copper production used in the manufacturing stage contribute 40% to this impact. Installation, operation and maintenance each contribute 20% to the total, mainly due to the transport of the system to site, the electricity used to run the pump and the production of propylene glycol.

3.1.10. Terrestrial eco-toxicity potential (TETP)

The FPC system has a slightly higher TETP (3.41 g DCB eq./kWh) than ETC (3.38 g). The emissions of chromium to air from steel production during the manufacture of the systems are the major contributor (~90%).

3.2. Validation of the results

Although there are several LCA studies of solar thermal systems, comparison of the results among them is difficult, mainly due to different life cycle impact assessment (LCIA) methods used,

including the Eco-indicator and EPS 2000 methodologies [e.g. 19,23].

A further difficulty is related to the system boundaries – as discussed in the introduction, most studies have not considered the full life cycle of the solar thermal systems, omitting operation, maintenance and/or decommissioning [15–17,22,25]. Moreover, most studies have considered a limited number of impacts, notably energy use and global warming potential [14,19,21,22,25]. For these reasons, the comparison of the results obtained in this work with other studies is limited to three studies [15,16,24] which have used the same LCIA method and considered several impacts (although not the full range considered in the current work).

The comparison with the results obtained by Masrurah et al. [24] is shown in Fig. 5a. It should be noted that the solar thermal system considered in their study is different from the systems considered here as it includes (thermo-chemical) storage of heat. Furthermore, the study is based in France and Spain. Therefore a direct comparison between the two studies is not possible. Nevertheless, as can be seen in Fig. 5, the results of the two studies are comparable. For example, the average value of 0.21 g SO₂ eq./kWh reported for acidification in Ref. [24] is in close agreement with the values of 0.205 and 0.207 g SO₂ eq./kWh estimated in this study for the FPC and ETC systems, respectively. The GWP values also compare well: 34–38.5 g CO₂ eq./kWh estimated in the current work vs 22.7–36.0 g CO₂ eq./kWh in the study by Masrurah et al. [24]. The lower results in the latter could be due to the fact that the impact from the electricity for the pump in the operation stage has not been considered. However, the values for the eutrophication and photochemical oxidation potentials are on average 75% and 82% higher, respectively, compared to the values estimated by Masrurah and collaborators. This could be because the authors have not considered maintenance activities and electricity use in the operation stage. As shown in the previous section, both impacts are influenced by these two life cycle stages.

Fig. 5b compares the results from the current study with those obtained by Ardente and Corrado [16]. As the authors have not considered operation of the solar thermal systems, to enable comparison, the impacts arising from operation in our study have been subtracted from our overall results. Furthermore, the results in the current study have been converted and expressed per 1 collector as this is the functional unit used in Ref. [16]. As indicated in Fig. 5b, the results for acidification and global warming are in close agreement with differences of only 9% and 1%, respectively. However, the differences in eutrophication and photochemical

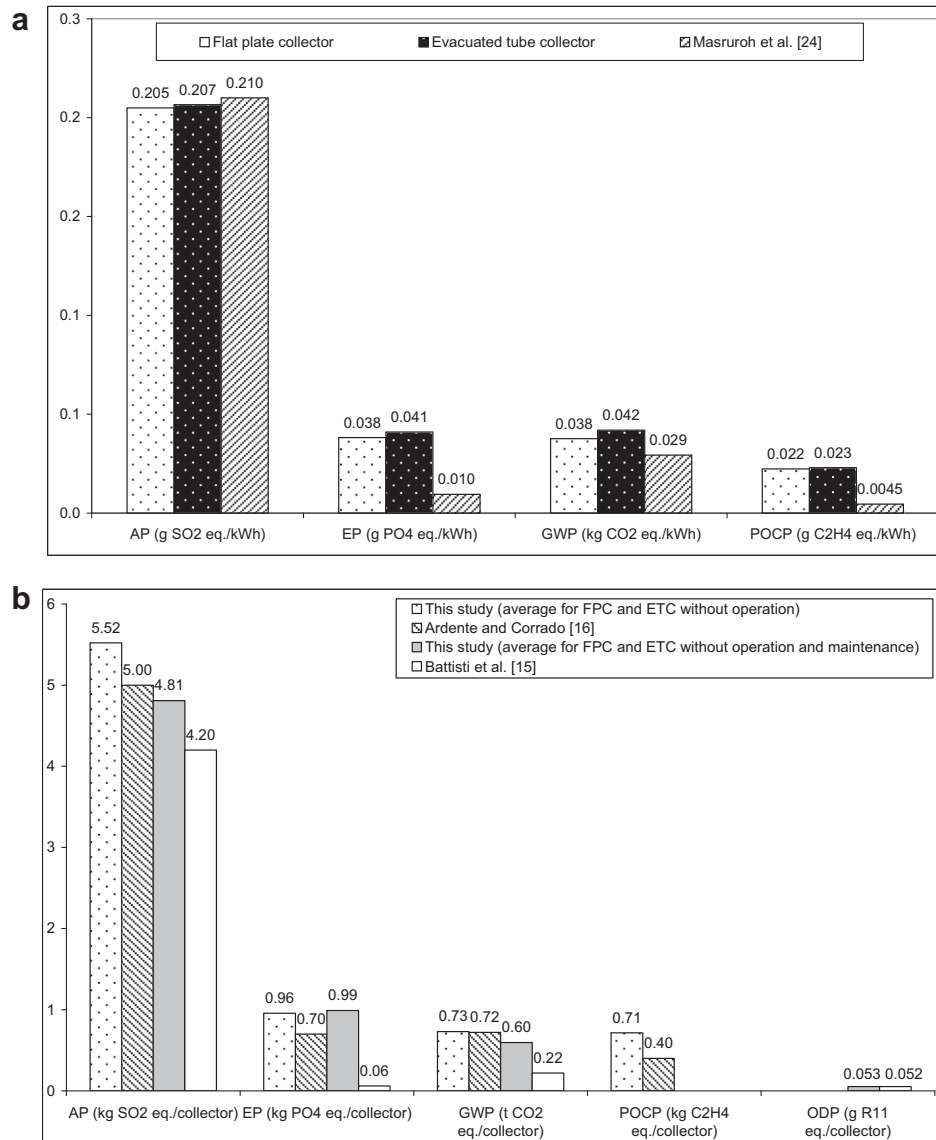


Fig. 5. Comparison of the results with the literature. a) Comparison of impacts per heat generated. [Masrurroh et al. [24] study excludes operation of solar thermal but includes a heat storage system. For impacts nomenclature see Fig. 2.] b) Comparison of impacts per collector. [System boundaries in Ardente and Corrado [16] exclude operation of solar thermal systems and in Battisti et al. [15] both the operation and maintenance are excluded. For impacts nomenclature see Fig. 2.]

oxidants are 27% and 44%, respectively. This can be attributed to the smaller size of the collector studied in Ref. [16]: 2.8 m² compared to 4.0 m² in this study.

Fig. 5b also compares the results of our study with that by Battisti et al. [15] who excluded both the operation and maintenance of the system. As above, the results of these stages for our study were subtracted from the overall results and compared to the results in Battisti et al. using their functional unit of the production of 1 collector. As shown in Fig. 5b, the results for acidification and ozone layer depletion are similar between the two studies, with differences of only 13% and 2%, respectively. However, the differences for eutrophication and global warming are significantly higher: 94% and 63%, respectively. Similar to the comparison with [16], these are mainly due to a much smaller size of the collector in the study by Battisti et al. [15]: 1.7 m² vs 4.0 m² in this study. This means that the steel content of the collector is much lower and hence are the eutrophication and global warming potentials which are influenced by this parameter (see Section 3.1).

Other studies [15,16,24,33] have also found that the manufacturing stage dominates the impacts due to the energy-intensive production of the steel and copper components (absorber, framework, pipework). Also, the results obtained by Hang et al. [14] support the findings of this study that the global warming potential of ETC is higher than FPC (11% higher in this study compared to 20–40% higher in their study).

3.3. Sensitivity analysis

The results suggest that the environmental performance of the solar thermal systems is sensitive to two key parameters: energy efficiency and the lifetime of the system. This is investigated below.

3.3.1. Reducing energy losses

Owing to the energy losses within solar thermal systems, only a small proportion – around 35% – of the solar energy collected is utilised. As stated previously, these losses occur throughout the

system, from reflection of incident radiation as it encounters the collector to losses as hot water is distributed for use. Here we investigate a reduction in energy loss in the range from 45% to 60% [25,31–33] to find out what effect that would have on the environmental performance of the solar thermal system compared to the 65% loss assumed in this study.

The results in Fig. 6 demonstrate that the environmental impacts of the two solar thermal systems could be reduced by 36% by reducing the current system energy losses from 65% to 45% (i.e. increasing the system efficiency from 35% to 55%). This applies uniformly to all the impacts as the amount of useful heat per functional unit increases. Further discussion on the implications of improved efficiency is provided in Section 3.4.1 which compares solar thermal systems with natural gas and electricity.

3.3.2. Lifetime of solar thermal systems

In the base case considered in this paper, a lifetime of 25 years for both solar thermal systems has been assumed, based on information from manufacturers. However, it is possible that the systems may need to be replaced sooner, for example, due to technical problems. It also may be the case that the systems operate successfully for more than 25 years. A sensitivity analysis has therefore been performed to determine how the assumed lifetime affects the environmental impacts.

The results suggest that shorter lifetimes of 15 and 20 years increase the environmental impacts of the solar systems on average by 48% and 18%, respectively. The biggest increases (>60% for a 15 year lifetime) are observed for the depletion of elements, freshwater and human toxicity potentials. This trend is illustrated for the example of FPC in Fig. 7. The reason for the higher impacts is the lower energy output over the lifetime relative to the materials input. A longer lifetime of 30 years would lead to around 10% lower environmental impacts, for the opposite reason.

3.4. Comparison with alternative water heating options

The results in Figs. 8 and 9 compare different alternatives to the solar thermal systems. This is discussed below for each alternative in turn. All comparisons are made over a period of 25 years (i.e. solar thermal lifetime) for a total heat of 38,500 kWh and scaled back to the functional unit of 1 kWh_{th}. This considers the replacement of the gas boiler every 12 years and the heat pumps after 20 years.

3.4.1. Natural gas boiler and electricity

As shown in Fig. 8, the solar thermal systems have lower impacts than the gas boiler for only five out of the 11 categories considered. For these categories, the solar systems save on average

70% of the impacts compared to the boiler, ranging from 21% for acidification to 93% for ozone layer depletion. The savings for global warming and depletion of fossil resources are 88% and 83%, respectively. Combustion of natural gas to generate the heat is the main cause of higher impacts compared to the solar thermal systems. On the other hand, all the toxicity-related potentials are higher for the solar thermal, with human and terrestrial toxicities being 85% higher, freshwater toxicity 78% and marine toxicity 70% worse than for the gas boiler. Depletion of elements is also 75% higher than for the gas boiler. This is mainly because of the high copper and steel content of the solar thermal systems, which results in high levels of heavy metal emissions.

If, however, energy losses from solar thermal systems are reduced to 50% (or the system efficiency is 50%), the FPC solar thermal system becomes comparable to the gas boiler for the eutrophication potential, which is reduced from 0.038 to 0.0267 g PO₄ eq./kWh (based on the results shown in Fig. 6; for the eutrophication potential of the boiler, see Fig. 8). For the ETC system, energy losses need to be reduced to 45% for eutrophication to become comparable or lower than that of a gas boiler. However, gas boiler remains the best option for all other environmental impacts (depletion of elements and all toxicity-related impacts) despite the reductions in energy losses.

Compared to the use of electricity for water heating, the solar thermal systems are environmentally more sustainable. For eight of the 11 categories considered the solar thermal systems have impacts on average 88% lower than for electricity, ranging from 66% for terrestrial toxicity to 93% for depletion of fossil fuels and global warming. The extraction, processing and combustion of fossil fuels to generate electricity is the main reason why the impacts for electricity are much higher. However, electricity has a lower impact than solar thermal for the depletion of elements (35%), freshwater (21%) and human (6%) toxicity. This is due to lower inputs of steel per kWh of heat produced as a result of its greater energy output compared to the solar thermal systems.

3.4.2. Heat pumps

The environmental impacts from solar thermal systems are compared to air, ground and water source heat pumps (ASHP, GSHP and WSHP, respectively) in Fig. 9. The life cycles of heat pumps are also from cradle to grave, comprising all the stages from manufacture and installation to operation, maintenance and decommissioning (for details, see Ref. [43]). The environmental impacts of heat pumps are based on the results reported in Greening and Azapagic [43], but adapted for the purposes of this work assuming that heat pumps are used for both space and water heating, of which 20,000 kWh/yr is used for the former and 3216 kWh/yr for the latter. Note that the amount of heat provided by the heat pumps corresponds to the average domestic demand and is higher than what solar thermal installations are able to generate (1540 kWh/yr as assumed here). This takes into account that heat pumps are self-sufficient and do not need a back-up gas boiler, as is the case with solar thermal systems (see Section 4.1 for further explanation).

The results indicate that solar thermal systems are environmentally more sustainable than heat pumps for seven out of 11 impacts considered, including global warming potential and fossil resource depletion. Compared to the ASHP, the environmental savings from the solar thermal systems are on average 71% lower, ranging from 41% lower eutrophication to 99.9% lower ozone layer depletion. A significantly lower electricity consumption (0.13 MJ/kWh) for operation of the solar thermal systems compared to the ASHP (1.35 MJ/kWh) is the main reason for these savings. However, depletion of elements, human toxicity, freshwater and terrestrial eco-toxicity are on average 49% lower for ASHP than for the solar

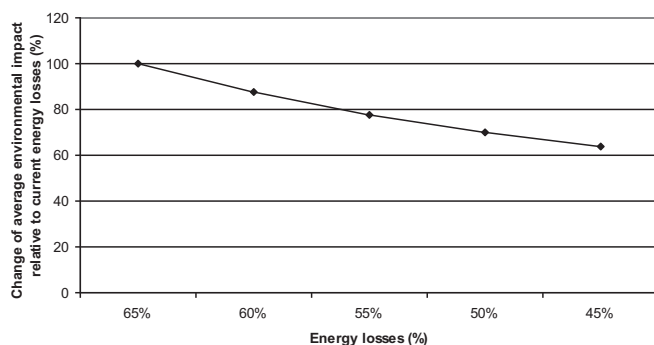


Fig. 6. The influence of solar thermal energy losses on the environmental impacts of the solar thermal systems.

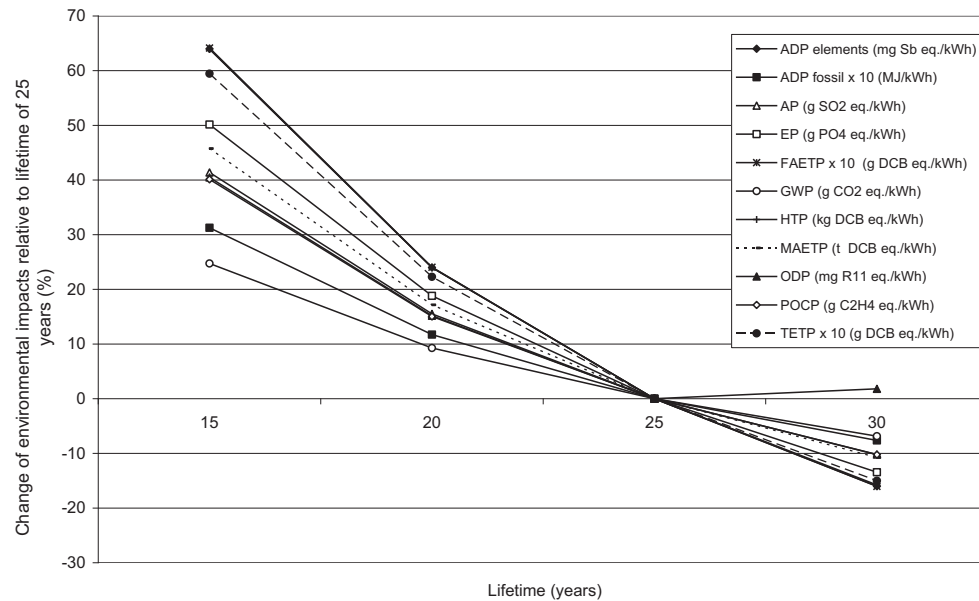


Fig. 7. The influence of lifetime on the environmental impacts of the FPC solar thermal system. [For impacts nomenclature, see Fig. 2.]

thermal systems. This is due to the impacts from the production of the solar glass and the selective coating.

The same pattern is observed for the ground-source heat pumps (GSHP) and water-source heat pumps (WSHP). For the categories for which the solar thermal systems perform better, impacts are on average 59% lower, ranging from 19% for eutrophication to 98% for ozone layer depletion. As for the ASHP, this is due to the higher electricity consumption by the GSHP and WSHP systems. On the other hand, the impacts which favour the heat pumps are on average 65% lower than for the solar thermal systems. These savings are greater than from the ASHP owing to a larger difference in the steel content between the solar thermal (140–152 kg) and ground- and water-source heat pump systems (~138 kg).

4. Environmental sustainability of solar thermal systems in the UK

The results of this study indicate that solar thermal panels are better for some environmental impacts but worse for the others in comparison to the current fossil-based water heating options. It is therefore important to understand the environmental implications at the national level if a large number of solar thermal systems are installed in the UK.

Currently, natural gas boilers are the main source of water heating in the UK, providing 84% of hot water [3]. In 2009, there were around 22.5 million gas boilers installed in the domestic sector, whilst there were only around 90,000 solar thermal installations [3,12,44]. In the

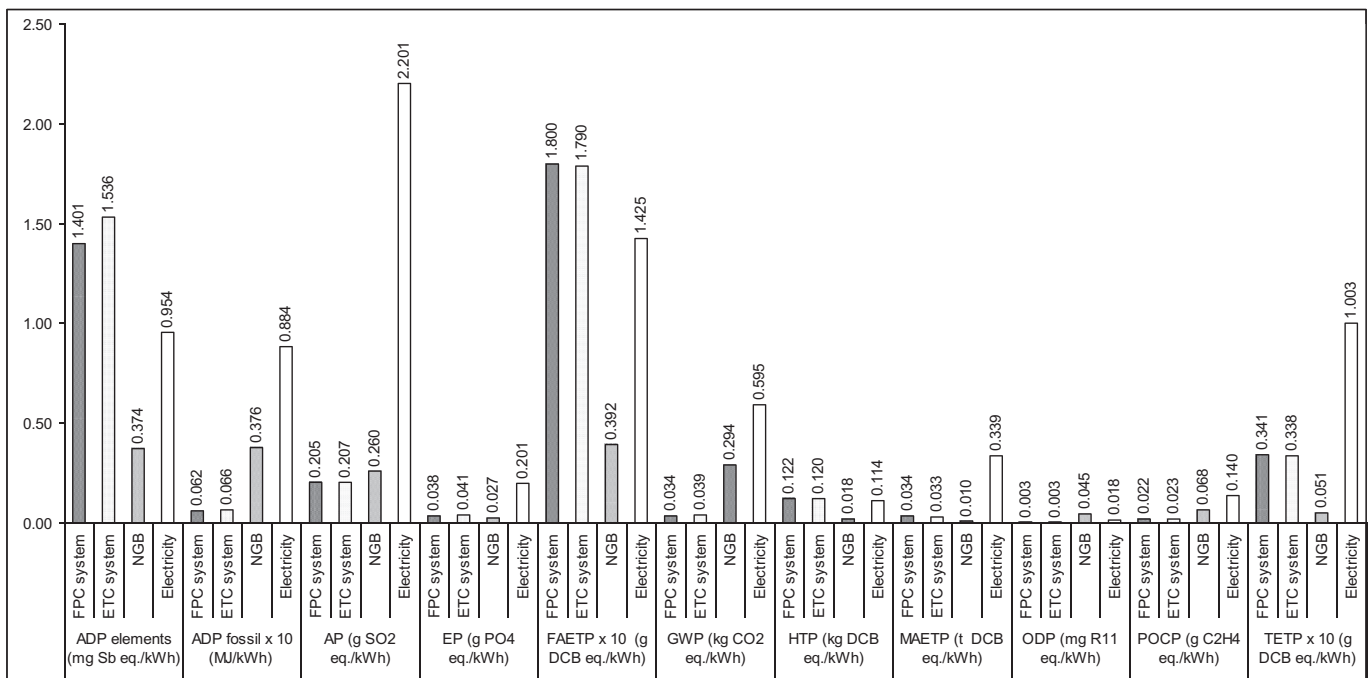


Fig. 8. Comparison of solar thermal systems with gas boiler and grid electricity heating. [For impacts nomenclature, see Fig. 2.]

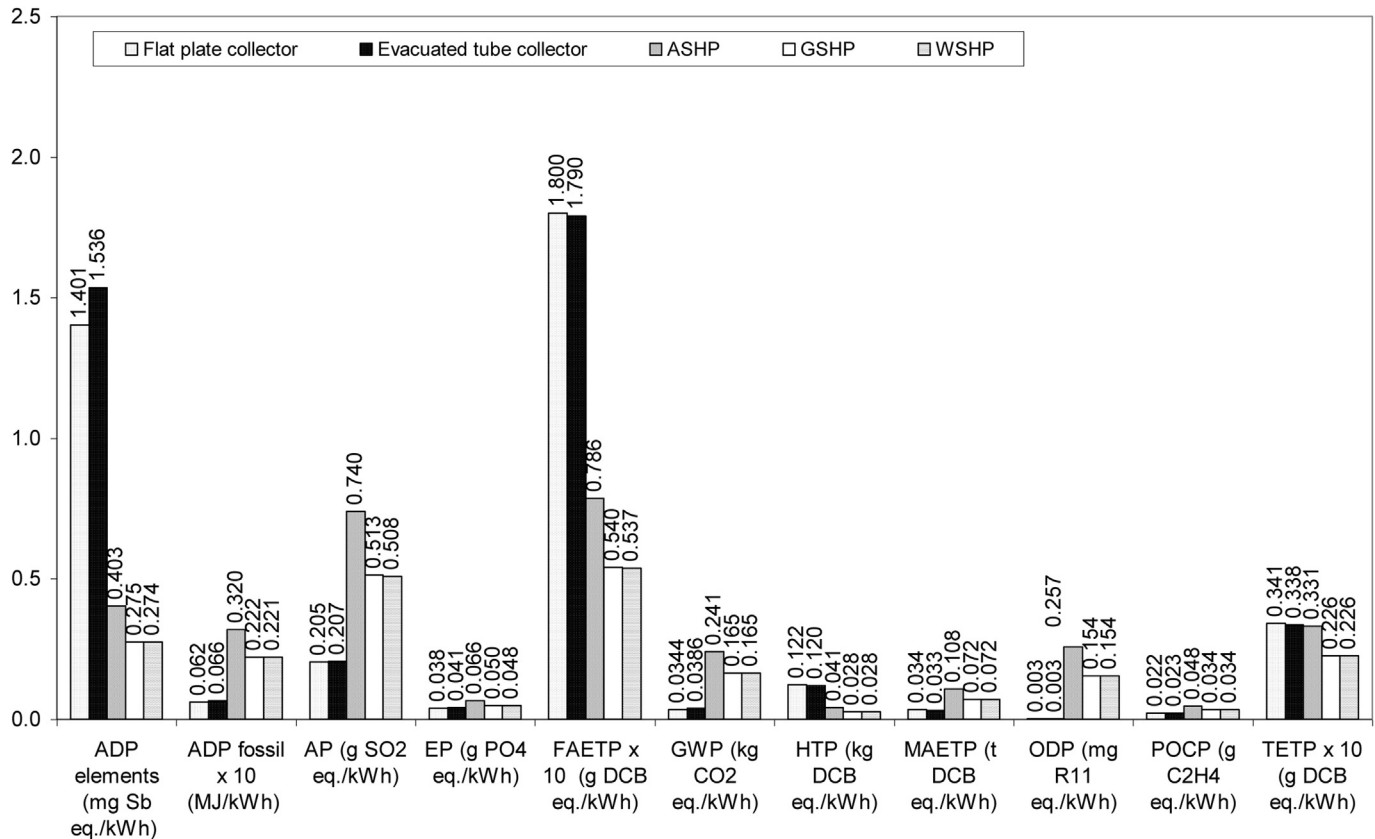


Fig. 9. Comparison of solar thermal systems with heat pumps. [ASHP: air-source heat pump; GSHP: ground-source heat pump; WSHP: water-source heat pump. Impacts for heat pumps adapted from Ref. [43] assuming that heat pumps are used for both space heating (20,000 kWh/yr) and water heating (3215 kWh/yr). For impacts nomenclature, see Fig. 2.]

same year the Energy Saving Trust estimated that without any further policy interventions there would be around 350,000 solar thermal installations by 2020 [45]. However, with further policy interventions in place – such as carbon pricing – they projected that up to 5 million units could be installed.

We therefore consider this ‘optimistic’ estimate of 5 million units of solar thermal systems installed in UK dwellings to examine the implications for the environmental sustainability of water heating in the UK. We first examine the total life cycle impacts, followed by an analysis of direct¹ GHG emissions to find out what potential contribution the solar thermal systems could make towards achieving the UK’s GHG emissions targets (as these are based on direct rather than life cycle emissions). Prior to that, the assumptions made for these estimates are outlined next.

4.1. Assumptions

The gas boiler is assumed to supply 100% of annual space (11,248 kWh) and water (3216 kWh) heating demand, when installed on its own. Thus, 22.5 million boilers will produce 325.4 TWh of heat per year. Assuming that each solar thermal system produces 1540 kWh of heat per year, 5 million units will produce 7.7 TWh/year. Therefore, when a solar thermal system is installed alongside a gas boiler, the boiler will supply the 1676 kWh of hot water demand not met by the solar thermal system. The 5 million installations of gas boilers (alongside solar thermal

systems) will produce 8.38 TWh/year of heat. Only gas boilers are considered as they supply the majority of domestic water heating (84% compared to <8% by electrical heating and the rest by oil boilers). It is assumed that all the boilers are condensing.

The life cycle impacts for 5 million solar thermal systems have been calculated by scaling up the impacts per kWh of heat delivered shown in Fig. 2 and taking into account the amount of heat delivered by each unit per year (1540 kWh). The back-up heat by gas (1675 kWh) has also been considered. The direct GHG emissions have been estimated in a similar manner. The methodology for these estimates is detailed in the Appendix.

4.2. Life cycle impacts

The total estimated annual life cycle environmental impacts are given in Fig. 10. As indicated, the installation and use of 5 million FPC or ETC systems would reduce the current global warming associated with the provision of hot water by gas boilers from 21.2 Mt CO₂ eq./year to 19.2 Mt CO₂ eq./year. This represents a saving of around 9%.

Around 9% of fossil fuels and 2% of the acidification potential would also be saved by installing the solar thermal systems alongside the gas boilers, whilst ozone layer depletion and creation of photochemical oxidants would be 10% and 7% lower, respectively, compared to providing hot water by gas boilers only.

However, some other impacts would increase with the installation of the solar thermal systems. Notably, depletion of abiotic elements would be 23–25% higher depending on the type of the solar thermal system and the toxicity-related impacts would increase on average by 26%, ranging from 4–5% for FAETP to 38–39% for HTP. The eutrophication potential would also go up by 4–5%.

¹ Direct emissions refer to those generated during the operation of an installation, as opposed to life cycle emissions which take into account emissions in the whole life cycle of an installation from ‘cradle to grave’.

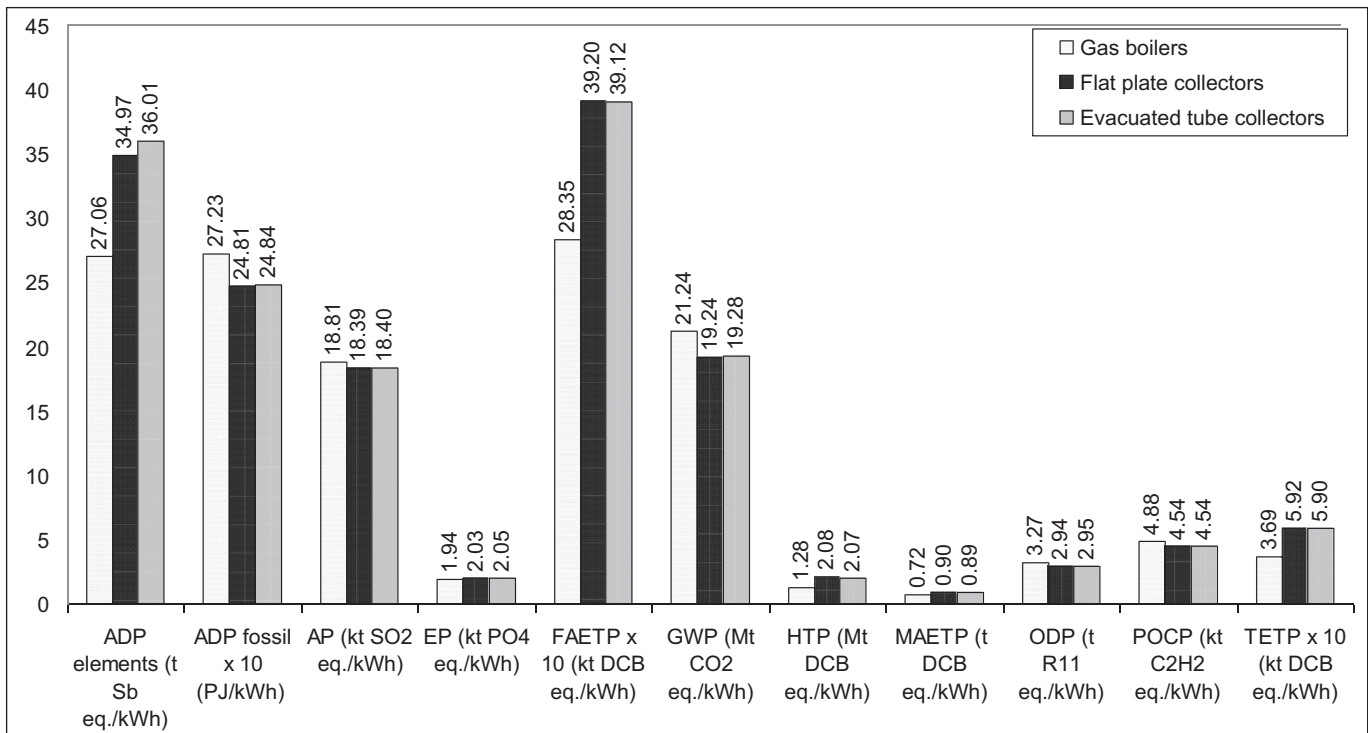


Fig. 10. Annual life cycle environmental impacts from domestic water heating with solar thermal systems installed alongside gas boilers, compared to gas boilers alone. [Flat plate collectors and evacuated tube collectors assume 5 million installations each, alongside 22.5 m gas boilers. For estimations, see the [Appendix](#). For impacts nomenclature, see [Fig. 2](#).]

4.3. Direct GHG emissions

National GHG emissions and the reduction targets refer to direct rather than life cycle GHG emissions. Therefore, to determine the potential contribution of solar water heaters to the UK climate change target of reducing GHG emissions by 34% by 2020, this section compares their direct CO₂ eq. emissions with the current sources of domestic hot water, i.e. grid electricity and gas boilers. For the estimates discussed below, see the [Appendix](#) and [Table 5](#).

In 2009, the GHG emissions from the domestic sector were 147.2 Mt CO₂ eq. [2]. Assuming all the boilers are condensing, the direct emissions from water heating via 22.5 million gas boilers in 2009 would have been 15.92 Mt CO₂ eq./yr. If solar thermal systems were installed in 5 million homes overnight alongside the existing gas boilers, whilst the remaining 17.5 million homes continued to use gas boilers for water heating, the direct emissions from domestic water heating would be 14.36 Mt CO₂ eq./yr. Thus, the total emissions from the domestic sector would be reduced by around 1%, from 147.2 Mt CO₂ eq./yr to 145.64 Mt CO₂ eq./yr.

To put this in the context of total national GHG emissions, in 1990 the UK emitted 778.3 Mt CO₂ eq. In 2009, a 27.24% reduction

in emissions (566.3 Mt CO₂ eq./yr) had been achieved. If, as assumed here, solar thermal systems offset 48% of water heating via gas boilers, the total emissions would decrease by 27.44% on the 1990 levels, leading to the total emissions of 564.74 Mt CO₂ eq./yr (see [Table 5](#)). This represents a 0.28% decrease on 2009 levels. Therefore, these results suggest that the potential of solar thermal systems to contribute towards the UK climate change targets is negligible.

5. Conclusions

The life cycle environmental impacts of two types of solar thermal systems used for domestic water heating have been estimated: flat plate and evacuated tube collectors. The results suggest that the former have lower environmental impacts on average by 7%. This is due to the greater energy requirements for the production of the evacuated tube collector system. Manufacturing is the main contributor (60%) to the environmental impacts associated with both the solar thermal systems, with steel and copper being the 'hot spots'. Therefore, reducing the amount of these metals used in the system or increasing the proportion of recycled

Table 5

Direct GHG emissions from the solar thermal systems and gas boilers (for estimates in this table, see the [Appendix](#)).

Water heating technology mix	Direct emissions (kg CO ₂ eq./kWh) ^a	Annual emissions from each water heating energy mix ^b (Mt CO ₂ eq./year)	Annual UK emissions from the domestic sector (Mt CO ₂ eq./year)	Total annual UK emissions in 2009 ^c (Mt CO ₂ eq./year)
Gas boilers (condensing) only	0.220	15.92	147.20	566.30
5 million homes with solar thermal + back-up gas boiler and 17.5 million homes with gas boilers only	Solar thermal: 0.017 Gas boiler: 0.220	14.36	145.64	564.74

^a Direct emissions for solar thermal systems include emissions associated with electricity generation. Source: Ecoinvent [39] and own estimates.

^b These values represent total UK annual emissions from water heating in the domestic sector, assuming in turn that solar thermal systems are installed in 5 million dwellings and offset 48% of water heating by gas boilers.

^c These values represent total UK annual emissions, assuming in turn that solar thermal systems are installed at 5 million dwellings offsetting 48% of hot water production via gas boilers.

steel and copper and/or replacing steel by recycled aluminium could help to reduce the impacts from manufacturing.

The operation stage is also important for some of the impacts, notably global warming potential and depletion of fossil resources, contributing up to 50% to these impacts.

Reducing the energy losses from the solar thermal systems could reduce the environmental impacts significantly. For example, reducing the current losses from 65% to 45% could lower the impacts by around 35%. However, reductions in energy losses have little effect on improving performance of the solar systems over the gas boilers. Further improvements in environmental impacts can be achieved with longer lifetimes. If operated for longer than 25 years, the impacts would be reduced by 10% for a 30 year lifetime. However, shorter lifetimes could increase the impacts by 18% for a 20 year and 48% for a 15 year lifetime compared to 25 years.

The results from this study also show that solar thermal systems do not necessarily represent an environmentally more sustainable alternative to fossil fuel-based water heating. For example, they have lower impacts than the gas boiler for only five out of the 11 categories considered. These include global warming potential which is reduced by 88% and fossil fuel depletion which is 83% lower than from the gas boiler system. However, the majority of other environmental impacts, including human and eco-toxicity, are increased on average by 71%.

The solar thermal systems compare better to electrical water heating. For eight of the 11 categories considered, their impacts are on average 88% lower than electrical water heating, ranging from 66% for terrestrial toxicity to 93% for depletion of fossil fuels and global warming. However, electricity has lower depletion of elements (by 35%), freshwater (21%) and human toxicity (6%).

Compared to the different types of heat pump (air-, ground- and water-source), both types of solar thermal system are more sustainable for seven out of 11 impacts, saving on average between 59% and 72% of these impacts relative to heat pumps. This includes savings in fossil fuel depletion (76%) and global warming (81%). However, for depletion of elements, human, freshwater and terrestrial toxicity, heat pumps are a better option than solar thermal systems, saving on average 49% (air-source heat pumps) and 65% (ground- and water-source heat pumps).

If solar thermal systems were to be deployed on a larger scale across the UK, the results indicate that 5 million installations would save around 9% of the global warming potential and fossil fuels compared to the current situation. Ozone layer depletion and creation of photochemical oxidants would be 10% and 7% lower, respectively, compared to providing hot water by gas boilers only. On the other hand, depletion of abiotic elements and the toxicity-related impacts would increase on average by 25%.

Considering only direct GHG emissions, the total CO₂ eq. emissions arising from the domestic sector would only decrease by around 1% when 5 million solar thermal systems are installed for water heating. In terms of the total UK GHG emissions, the use of solar thermal systems would only lead to a reduction of 0.28% of direct GHG emissions.

Therefore, these results show that the use of solar thermal systems could help reduce some of the impacts but would also worsen others, particularly compared to gas boilers. Although per unit of heat delivered they have much lower global warming potential than the fossil-based alternatives, their contribution to UK climate change targets would be minimal due to the lack of suitable locations in the UK and their limited energy output, which means back-up sources of heat are still required.

In conclusion, the very small contributions to UK's GHG targets between now and 2020 as well as an increase in some of the impacts, notably human and eco-toxicity, suggest that it is unlikely that solar thermal systems can contribute to a more sustainable domestic energy supply in the UK.

Acknowledgements

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Appendix

The following outlines the methodology for estimating the life cycle impacts and direct GHG emissions associated with the deployment of 5 million solar thermal systems in the UK.

A1. Estimation of life cycle impacts

The annual life cycle impacts of water heating with and without the solar thermal systems have been calculated as follows:

- i) With solar thermal systems
 - 5 million solar thermal (ST) units, providing 48% of water heating needs (1540 kWh/yr):
 - (1) *Annual life cycle impact (t eq./yr) = Number of ST (5 million) × heat supplied by ST (1540 kWh/yr) × life cycle impact of ST per kWh (t eq./kWh)*
 - An equivalent number (5 million) of natural gas boilers (NGB) providing the remaining 52% of water heating needs (1676 kWh/yr):
 - (2) *Annual life cycle impact (t eq./yr) = Number of NGB (5 million) × remaining heat supplied by NGB (1676 kWh/yr) × life cycle impact of NGB per kWh (t eq./kWh)*
 - The remaining number of NGB (22.5 m–5 m = 17.5 m) providing the full annual heat demand (3216 kWh/yr):
 - (3) *Annual life cycle impact (t eq./yr) = Number of NGB (17.5 million) × full annual heat demand provided by NGB (3216 kWh/yr) × life cycle impact of NGB per kWh (t eq./kWh)*
 - Total life cycle impacts of solar thermal systems and gas boilers:
 - (4) *Total life cycle impacts (ST + NGB) = (1) + (2) + (3).*
- ii) Without solar thermal systems
 - Total number of NGB (22.5 m) providing the full annual heat demand (3216 kWh/yr):
 - (5) *Annual life cycle impact (t eq./yr) = Number of NGB (22.5 million) × full annual heat demand provided by NGB (3216 kWh/yr) × life cycle impact of NGB per kWh (t eq./kWh)*

The results of (4) and (5) are then compared to estimate the difference in life cycle environmental impacts with and without solar thermal systems.

A2. Estimation of direct GHG emissions

For estimations detailed below, see also data in [Table 5](#).

- i) Without solar thermal systems
 - Total number of NGB (22.5 m) providing the full annual heat demand (3216 kWh/yr):
 - (1) *Annual direct GHG emissions from NGB (Mt CO₂ eq./yr) = Number of NGB (22.5 million) × full annual heat demand provided by NGB (3216 kWh/yr) × CO₂ emissions from NGB per kWh (0.22 kg CO₂ eq./kWh) × 10^{−6} (Mt) = 15.92 Mt CO₂ eq./yr*
 - Emissions from the domestic sector other than water heating:

- (2) *Emissions from the domestic sector without water heating* ($\text{Mt CO}_2 \text{ eq./yr}$) = *Total emissions from the domestic sector* ($147.2 \text{ Mt CO}_2 \text{ eq./yr}$) – *Annual direct CO}_2 \text{ emissions from NGB}* ($15.92 \text{ Mt CO}_2 \text{ eq./yr}$) = $131.28 \text{ Mt CO}_2 \text{ eq./yr}$
- Emissions from sectors other than domestic:
 - (3) *Emissions from other sectors* ($\text{Mt CO}_2 \text{ eq./yr}$) = *Total UK annual emissions* ($566.3 \text{ Mt CO}_2 \text{ eq./yr}$) – *Annual direct CO}_2 \text{ emissions from the domestic sector}* ($147.2 \text{ Mt CO}_2 \text{ eq./yr}$) = $419.1 \text{ Mt CO}_2 \text{ eq./yr}$
- ii) With solar thermal systems
 - Total number of ST (5 m) providing the annual heat demand (1540 kWh/yr):
 - (4) *Annual direct GHG emissions from ST* ($\text{Mt CO}_2 \text{ eq./yr}$) = *Number of ST (5 million)* \times *annual heat demand provided by ST* (1540 kWh/yr) \times *CO}_2 \text{ emissions from ST per kWh}* ($0.017 \text{ kg CO}_2 \text{ eq./kWh}$) $\times 10^{-6} (\text{Mt}) = 0.131 \text{ Mt CO}_2 \text{ eq./yr}$
 - An equivalent number (5 million) of natural gas boilers (NGB) providing the remaining 52% of water heating needs (1676 kWh/yr):
 - (5) *Annual direct GHG emissions from NGB* ($\text{Mt CO}_2 \text{ eq./yr}$) = *Number of NGB (5 million)* \times *remaining heat supplied by NGB* (1676 kWh/yr) \times *direct CO}_2 \text{ emissions from NGB per kWh}* ($0.22 \text{ kg CO}_2 \text{ eq./kWh}$) $\times 10^{-6} (\text{Mt}) = 1.84 \text{ Mt CO}_2 \text{ eq./yr}$
 - The remaining number of NGB ($22.5 \text{ m} - 5 \text{ m} = 17.5 \text{ m}$) providing the full annual heat demand (3216 kWh/yr):
 - (6) *Annual direct GHG emissions* ($\text{Mt CO}_2 \text{ eq./yr}$) = *Number of NGB* (17.5 million) \times *full annual heat demand provided by NGB* (3216 kWh/yr) \times *direct CO}_2 \text{ emissions from NGB per kWh}* ($0.22 \text{ kg CO}_2 \text{ eq./kWh}$) $\times 10^{-6} (\text{Mt}) = 12.38 \text{ Mt CO}_2 \text{ eq./yr}$
 - Total life cycle impacts of solar thermal systems and gas boilers:
 - (7) *Total direct GHG emissions from ST and NGB* ($\text{Mt CO}_2 \text{ eq./yr}$) = (4) + (5) + (6) = $0.13 \text{ Mt CO}_2 \text{ eq./yr} + 1.84 \text{ Mt CO}_2 \text{ eq./yr} + 12.38 \text{ Mt CO}_2 \text{ eq./yr} = 14.36 \text{ Mt CO}_2 \text{ eq./yr}$
 - Total domestic emissions other than water heating when solar thermal is considered as part of the water heating technology mix:
 - (8) *Total domestic emissions with ST considered* ($\text{Mt CO}_2 \text{ eq./yr}$) = (2) + (7) = $131.28 \text{ Mt CO}_2 \text{ eq./yr} + 14.36 \text{ Mt CO}_2 \text{ eq./yr} = 145.64 \text{ Mt CO}_2 \text{ eq./yr}$
 - Total UK GHG emissions for all sectors when solar thermal is considered as part of the water heating technology mix:
 - (9) *Emissions from other sectors with ST included in the energy mix* ($\text{Mt CO}_2 \text{ eq./yr}$) = (3) + (8) = $419.1 \text{ Mt CO}_2 \text{ eq./yr} + 145.64 \text{ Mt CO}_2 \text{ eq./yr} = 564.74 \text{ Mt CO}_2 \text{ eq./yr}$

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