Environmental assessment of industrial solar thermal systems

Paris A. Fokaides[1], Rokas Valancius[2], Angeliki Kylili[1], Andreas Ioannides[3], Manolis Souliotis[4], Andrius Jurelionis[2] and Soteris Kalogirou[5]

[1] Frederick University, Nicosia (Cyprus)

[2] Kaunas University of Technology, Kaunas (Lithuania)

[3] Johnsun Heaters Ltd, Nicosia (Cyprus)

[4] University of Western Macedonia, Kozani (Greece)

[5] Cyprus University of Technology, Limassol (Cyprus)

Abstract

European figures indicate that the deployment of solar thermal technologies for the supply of hot water is limited to the domestic sector, leaving untapped a large potential that could be exploited by the industrial sector. This work aims to describe the development of industrial solar thermal system penetration scenarios, in an effort to inform about the magnitude of this unexploited potential for Europe. For this purpose, the environmental performance of large-scale industrial solar thermal systems was quantified through the use of life cycle assessment (LCA) tools. A parametric LCA for two European locations allowed the definition of the relationship between solar potential and the system's environmental performance. The results concerning the carbon-saving potential of the industrial application of solar thermal systems were assessed, with reference to the European Emissions Trading System for the development of European penetration scenarios, as well as appropriate country-based incentives for encouraging their deployment in the industrial sector.

Keywords: Solar thermal system, flat plate collector, industrial sector, Life Cycle Assessment, Emissions Trading System

1. Introduction

While solar thermal technologies are widely used in domestic applications across Europe, their application in the industrial sector is still at a low level. The generation of process heat from solar thermal systems has enormous potential, which can satisfy a substantial amount of heat demand for industrial processes. In fact, there is technical potential to provide around 15 EJ of solar thermal heat by 2030, while the share of solar thermal deployed in the industrial sector could reach 33% (IRENA, 2014). This potential is also anticipated to significantly support the industrial sector in achieving its greenhouse gas (GHG) emissions mitigation, under the European Union Emissions Trading System (EU ETS), and could also contribute to meeting Europe's 2020 energy and climate targets. At present in Europe, however, only a small percentage of installations for process heat have collector areas exceeding 1000 m^2 (ESTIF, 2015).

The main focus of this study was the implementation of the life cycle assessment (LCA) of industrial solar thermal systems (ISTSs), with the purpose of quantifying and monetising their carbon-saving potential. The findings of the environmental performance of ISTSs, considering geographic location and solar potential, were assessed in relation to the EU ETS for the development of scenarios of ISTS penetration into the industrial sector. In conclusion, this work suggests appropriate incentives for the successful deployment of these systems in Europe.

2. Background information

2.1. Industrial application of solar water heating

Solar thermal systems for water heating are predominantly suitable for application in industries that utilise water in the low-temperature range of 40°C to 80°C and that have low energy requirements. Such industries include the food industry, agro-industries, textiles, the chemical industry and the beverage industry (Karagiorgas et al., 2001;

doi:10.18086/eurosun2018.08.08 Available at http://proceedings.ises.org

Kalogirou, 2002). Due to their low cost and simple construction, Muneer et al. (2006) proposed the introduction of built-in-storage water heaters, units that combine a flat-plate collector and a storage tank in one system, for application in the textile industry. Using the model of an Austrian dairy plant, Schnitzer et al. (2007) demonstrated that a solar field of 1000 m^2 can achieve annual natural gas savings of 85,000 m^3 and carbon savings of 170 tonnes of CO_2, with a return on the investment in less than three years. Kalogirou and Tripanagnostopoulos (2007) introduced a new hybrid photovoltaic/thermal system for low-temperature industrial application, which proved to cover a great percentage of the thermal energy required for the industrial process, as well as generating electricity.

Beyond this application, potential has also been identified for solar thermal energy at medium and medium to high temperatures that would satisfy the temperature requirements of industrial solar process heat applications (60°C to 260°C) (Kalogirou, 2002, 2003, 2004). It has been indicated that using parabolic trough collectors can satisfy half of the annual load, achieving annual energy savings of 896 GJ and carbon savings of 208 tonnes of CO_2-equivalent (Kalogirou, 2002). The same study also revealed that greater savings were achieved with larger loads. In addition, Kalogirou (2003) assessed a variety of solar thermal systems for providing industrial process heat with energy generation ranging between 550 and 1100 kWh/m^2/a, depending on the type of solar collector. A novel methodology – a design space approach – was proposed by Kulkarni et al. (2007, 2008) for the design and optimisation of flat-plate solar-collector-based systems and concentrating-solar collector-based systems for both low- and medium-temperature industrial applications. The proposed methodology was demonstrated through a case study of a dairy plant, where a 23% reduction in total system costs could be realised, compared to the existing design.

2.2. LCA of solar water heating

Solar thermal systems exploit a renewable energy source whilst essentially emitting zero emissions during their life-cycle operation phase. This has led to the implementation of a considerable number of LCA studies, the focus of which has been on quantification of the environmental impact of such systems throughout their life-cycles. In a recent study, the use of biomass as fuel for the auxiliary system in solar water heating systems demonstrated the best performance, in terms of kilograms of CO_2-equivalent, among 32 different types of solar water heating systems (Zambrana-Vasquez et al., 2015). Several studies have employed LCAs related to the environmental impact of two types of solar thermal systems that have traditionally been used for domestic water heating – flat-plate and evacuated-tube collectors (Hang et al., 2012; Carlsson et al., 2014; Greening and Azapagic, 2014). Hang et al. (2012) indicated that the flat-plate solar water heating system, using a natural gas auxiliary heater, was the best performing system among all the investigated types of auxiliary systems and locations, while Greening and Azapagic (2014) indicated a better performance of evacuated-tube collectors in regions with low solar irradiation, such as the UK. Additional studies also exist that have investigated the environmental performance of novel solar thermal collector concepts through LCA methodologies (Otanicar and Golden, 2009; Lamnatou et al., 2014, 2015; Comodi et al., 2014; Carnevale et al., 2014).

Researchers have also investigated the life-cycle performance of solar thermal systems from an environmental perspective, using the life cycle costing (LCC) methodology. Hang et al. (2012) calculated the LCC payback for solar water heating systems, finding it to vary from four to 13 years, depending on geographical location and type of solar collector, using the conventional electrical water heating system as the reference case. In Carlsson et al. (2014), where a solar heating system with polymeric solar collectors was compared to two equivalent solar heating systems (with flat-plate and evacuated-tube solar collectors), using both LCA and LCC, the economic analysis indicated that, despite the environmental advantage of the novel system, in terms of costs per amount of solar heat collected, the differences between the three types of collector systems were small, considering the given energy prices and environmental tax rates.

2.3. European policy on support schemes for the promotion of RES and Energy Efficiency

The EU is taking action in several areas to meet its climate and energy targets under the 2020 package. The main objective of the Renewable Energy Directive (2009/28/EC) for a 20% RES contribution to the EU's total energy demand will be achieved through the fulfilment of national renewable targets, as set out in the National Action Plan (NAP). In acknowledging that each Member State has different renewable energy potentials, tailored support schemes and measures have to be developed to meet national targets. In several cases, RES support schemes that have been successfully implemented in one country, have failed in another (Kylili and Fokaides, 2015; Pyrgou et al., 2016). The rationalisation of national support schemes is also considered important, so that investor confidence is maintained and schemes are effectively implemented.

As far as the contribution of the industrial sector to meeting the climate and energy targets is concerned, the EU has established the EU ETS (2003/87/EC, 2009/29/EC). This is the EU's key tool for cutting GHG emissions from large-scale facilities in the power, industrial and aviation sectors, involving a 'cap and trade' system, where the total volume of GHG emissions from the aforementioned sectors that are responsible for 45% of European GHG emissions, is capped. The relevant legislation creates allowances, which are essentially rights to emit GHG emissions equivalent to the global warming potential of 1 tonne of CO_2-equivalent. The scheme allows the trading of emission allowances, with the purpose of keeping the total emissions of the installations and aircraft operators below the cap, which tightens over time, and ensuring that emissions are reduced where it is most cost-effective. As a result, the trading allows the carbon price to meet the desired target.

3. Methodology

3.1. Methodology overview

The methodology followed in this work was based on the implementation of a LCA on an ISTS for environmental assessment of the different components that make up the systems, including the flat-plate collectors, storage tank and other auxiliary components. Definition of the environmental impact of ISTSs allows its comparison to conventional water heating systems (CWHS), as well as the conduction of a parametric analysis for specific European locations of diverse solar potential. Taking into consideration the quantified carbon savings from the application of ISTSs, and in relation to the EU ETS, scenarios of ISTS penetration and monetisation in the industrial sector were developed. In light of that, the study included the definition of appropriate incentives for ISTS penetration for diverse locations in Europe. The methodology followed in this study is illustrated in Figure 1.

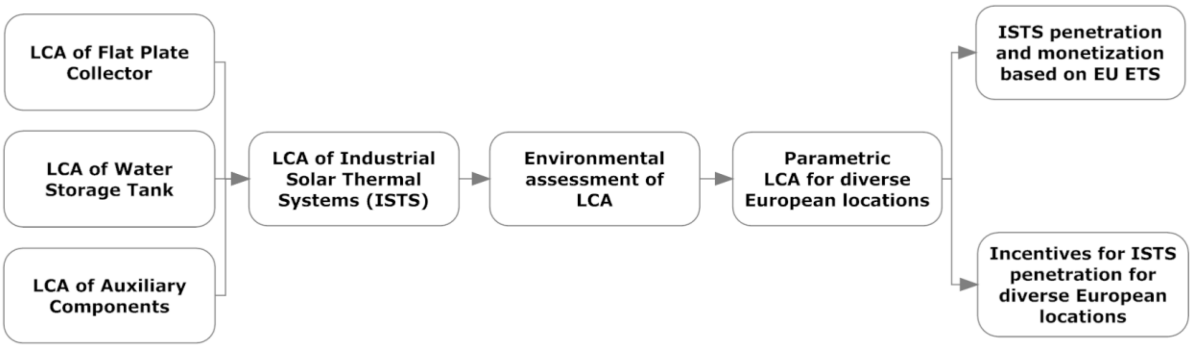

Fig. 1: Graphic representation of the methodology of the study

3.2. Life Cycle Assessment Scope and Inventory

The definition of the environmental performance of solar thermal water heating systems for industrial applications is achieved through the adoption of the standardized LCA approach, provided by the ISO 14040 series, and the employment of one of the most well- established LCA tools currently available — GaBi software (ISO 14040:2006; Thinkstep GaBi., 2017). The investigated solar thermal water heating systems were pre-engineered to satisfy the temperature requirements of industrial processes concerning low temperature hot water up to 100 °C (Kalogirou, 2004). Taking into consideration the installed capacity of existing ISTS which exploit flat plate collector technology for water heating purposes (IEA, 2016), the functional unit (FU) has been defined (Table 1). The functional units included the system which is comprised from the solar collectors, storage tanks, mounting equipment, pipes, hydraulic components, auxiliary heating and the solar fluid. The data for the development of the LCI has been obtained from the manufacturers and/ or importers of the components that make up the solar thermal systems; whereas for those components primary data were not available, secondary data from well-established LCI databases has been used. In this study, a cradle to use analysis was implemented; the system boundaries are illustrated in Figure 2.

Tab. 1: Functional unit (FU) employed for the LCA of Industrial Solar Thermal System (ISTS)

Installed thermal power [kWth]	Installed collector area [m²], gross	Aperture area [m²]	Number of solar collectors	Number of water storage tanks
70	100	92	41	9

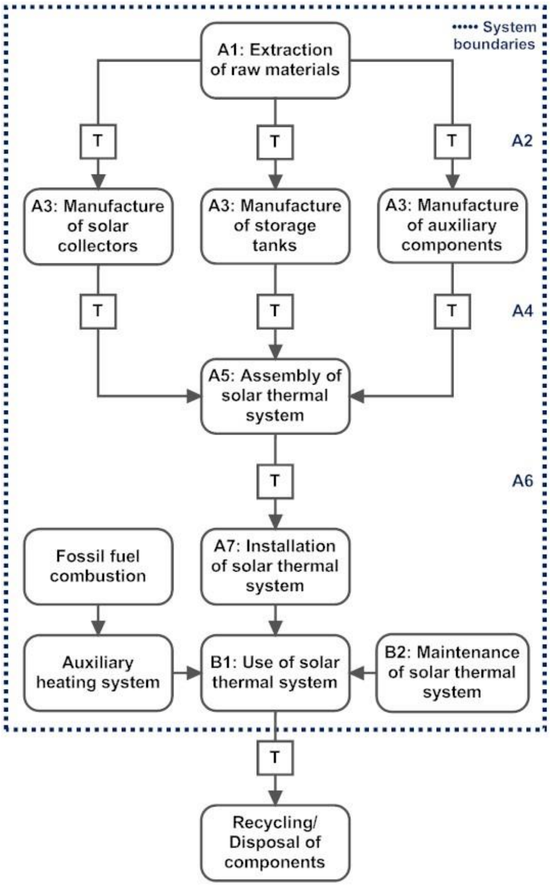

Fig. 2: Life Cycle Assessment – System Boundaries (T: Transportation – A2, A4, A6

The assumptions made for the environmental analysis are the following:

- Cyprus is the reference geographical area for the manufacturing of the solar thermal system. The origin of the different system components was considered as follows (Johnsun Heaters Ltd, 2016):
  - Absorber Plate: Germany
  - Back cover and framework: Egypt
  - Headers and risers: Bulgaria
  - Glass wool and tempered glass: Greece
  - EPDM: Cyprus
- A parametric investigation of the impact of the distance between the assembly and the installation point was not considered as a requirement, as the impact of this parameter was found to be negligible.
- The life span of the solar thermal system was assumed to be 20 years.
- The use phase of the system included the fossil fuel combustion for auxiliary heating, while its maintenance included the annual drainage and refilling of the solar fluid over its lifetime.
- Propylene glycol was considered as the solar fluid.
- The auxiliary heating was assumed to be through fossil-fuelled boiler, representing a CWHS. The manufacturing of the auxiliary heating source (boiler) was also considered.

The findings of the LCA on the environmental impact of the investigated ISTS were evaluated with respect to the environmental performance of equivalent capacity of CWHS, ie., fossil-fueled boilers. The performance of the ISTS was also assessed under two climatic conditions —warmer (Athens) and colder climates (Frankfurt aM)— given that its performance would be affected by the solar potential of the installation location. The annual energy contribution of the ISTS and the auxiliary hot water system per kWth for each considered location was defined through the employment of the TSOL software (Valentin software, 2017) (Table 2).

Tab. 2: Energy contributions of the ISTS and the auxiliary conventional water heating systems in investigated sites

Location	System energy contribution per kW per annum	
	ISTS	**Auxiliary CHWS**
Athens (37.9˚ lat.)	879	229
Frankfurt aM (50.1˚ lat.)	552	557

3.3. Life Cycle Costing and Support Schemes

In terms of this study, the potential support schemes, in the form of investment aids, were defined by considering the equivalent cost of carbon savings from the application of ISTS and in relevance to the EU ETS. For the calculation of the carbon monetary value, the price of carbon was set at 10.32 €/ tn CO_2, representing the average cost for carbon since January 1st, 2008 (Investing.com, 2017). The costing of the investigated ISTS was performed based on price indicators retrieved from ESTIF (2015), as well as based on LCC principles described in Kalogirou

(2013) and Fokaides and Kylili (2014). For the development of the scenarios of ISTS penetration and the implementation of the LCC, actual data of the total final consumption of the industrial sector for each of the investigated locations has been retrieved from the International Energy Agency (EIA, 2017). This concludes to incentives' recommendations for the development of support schemes of ISTS in the considered energy mixes.

4. Results and Discussion

4.1. Life Cycle Impact Assessment (LCIA) of Industrial Solar Thermal Systems (ISTS)

The LCIA results, illustrated in Figure 3 for Athens, reveal the percentage contribution of each life-cycle stage on the total environmental impact of ISTSs. In both locations, the results demonstrate that the life-cycle phases of the investigated ISTSs that are the most detrimental to the environment are the raw material extraction, the system manufacturing phase and the use phase. In terms of impact, the raw material extraction and system manufacturing phases contribute to more than 84% of the total in the categories of ozone and element depletion, as well as the ecotoxicity to human health and the marine and terrestrial environments. As a result of fossil fuel combustion (natural gas) in the auxiliary heating system for the generation of hot water, the use phase is presented as having a principal contributing role in the potential for global warming and ocean acidification and eutrophication, depletion of fossil fuels, and the creation of photochemical ozone in the troposphere, amounting to 67% to 81%. The installation of such systems is also worth noting, contributing 9% to the ocean acidification potential, 6% to the terrestrial ecotoxicity potential, and 5% to the photochemical ozone creation potential. Regarding the rest of the phases included in the system boundaries of this work – transportation of the system and system components, and maintenance of the system – their contribution to the totals are negligible.

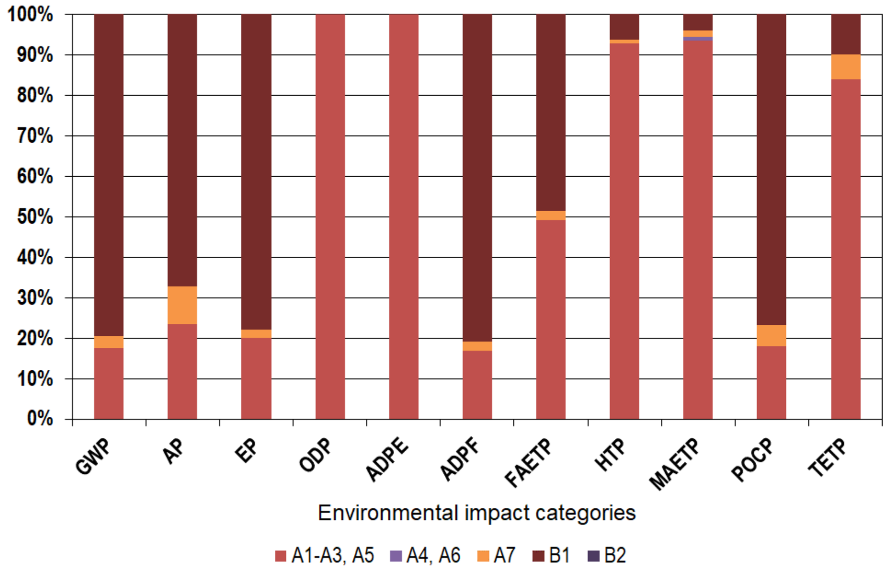

Fig. 3: Life Cycle Impact Assessment of ISTS located in Athens per life cycle stage

The environmental impact of ISTSs was also comparatively assessed against the CWHS of equivalent system output, taking into consideration the same system boundaries. The potential of ISTSs is less than one-third of the conventional equivalent system for the categories of climate change, ocean acidification and eutrophication, depletion of fossil fuels and photochemical ozone creation. The potential in the respected categories for the conventional system can be largely related to the fossil fuel combustion during its manufacturing and use phases; however, the comparative analysis results also revealed significant pressure on the environment caused by manufacturing of the ISTSs, especially in terms of the abiotic depletion of elements and ecotoxicity to human health. For these specific categories, the potential of ISTSs is considerably higher than its conventional equivalent system, by a factor of 400 and 30, respectively. By taking into consideration the life-cycle phases in the defined system boundaries, the non-renewable energy sources and CO_2 balances for both systems were also extracted using GaBi software.

4.2. Parametric Life Cycle Impact Assessment (LCIA) results for diverse locations

The parametric LCA analysis indicated that the environmental burden of ISTSs found in locations of lower solar potential was higher in the majority of environmental categories than systems located at southern latitudes (Table 3). The reasoning directs to the use phase of the system, and the fact that ISTSs located in areas of high solar potential (i.e., Athens) can generate higher energy yields for the supply of hot process water, while the use of the auxiliary system, along with the fossil fuel consumption, is substantially reduced.

Tab. 3: Life Cycle Impact Assessment (LCIA) results per kWth of ISTS for the two investigated locations

Environmental impact categories	Athens	Frankfurt aM
GWP	1,82E+03	3,75E+03
AP	5,44E+00	5,10E+00
EP	5,10E-01	5,92E-01
ODP	9,81E-03	1,05E-02
ADPE	6,54E-02	6,55E-02
ADPF	2,46E+04	5,14E+04
FAETP	1,24E+01	2,41E+01
HTP	8,54E+02	8,99E+02
MAETP	4,00E+05	4,29E+05
POCP	4,55E-01	5,54E-01
TETP	3,42E+00	3,29E+00

The overall non-renewable energy sources and CO_2 emissions for the considered sites, as well as the savings that can be achieved when compared to the CWHS, are presented in Table 4. In agreement with the LCIA results, location also has a decisive effect on the energy and carbon savings that can be achieved by large-scale ISTS applications.

Tab. 4: Life-Cycle energy and carbon emissions savings per kWth of ISTS for the two investigated locations

Site	Non-renewable energy consumption [GJ]	Energy Savings [GJ]	Carbon Emissions [ton CO_2]	Carbon Savings [ton CO_2]
Athens	27,21	75,32	1,74	4,95
Frankfurt aM	56,14	44,04	3,62	2,93

For the establishment of the relationship between latitude and ISTS energy performance, the same methodology was followed for four additional European locations — Barcelona, Milan, Copenhagen, and Oslo. This allowed the development of a 'life-cycle produced to consumed energy' ratio, where the impact of location on the energy performance of ISTS application was more profound (Figure 4). For the latitudinal range of 35˚ to 60˚, Figure 4 illustrates a strong inverse relationship between latitude and the ratio, with a higher ISTS location latitude equating to a lower 'life-cycle produced to consumed energy' ratio, and consequently a reduced system energy lifetime performance.

4.3. Scenarios of Industrial Solar Thermal Systems (ISTS) penetration

The results of the LCC of the considered ISTSs are provided in Table 5, where the saved carbon monetary value and the required number of ISTS applications of 700 kWth per penetration percentage are indicated. The values differentiate depending on the total final consumption of the industry of each country, as well as the potential energy saving per installed kWth. Greece has a lower (numerically) required capacity for ISTS applications of 700 kWth to satisfy national demand, as well as the lowest saved carbon monetary value per percentage of ISTS contribution to its energy mix. By considering the findings of Table 5, policy-makers can be guided towards providing appropriate financial incentives for large-scale ISTS applications, depending on the chosen national support scheme.

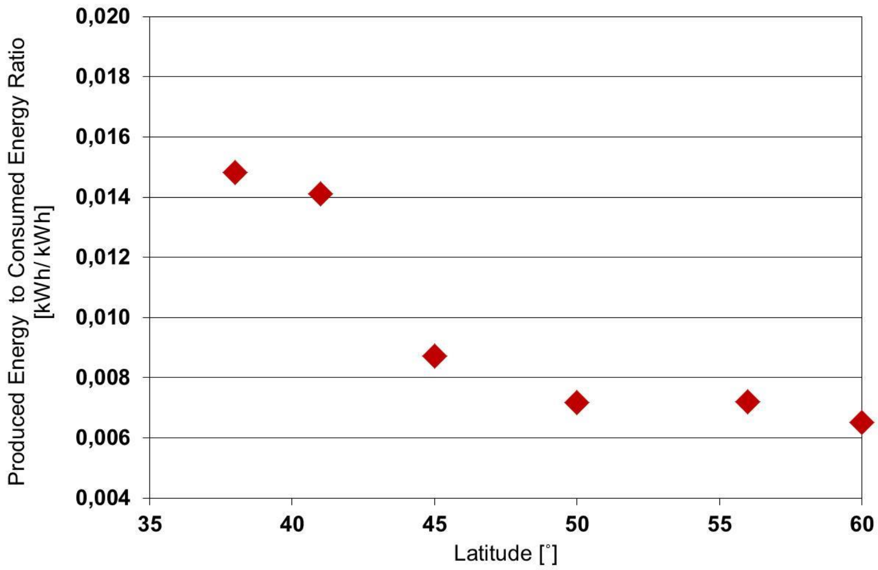

Fig. 4: 'Life-Cycle Produced to Consumed Energy' Ratio' for diverse European locations

Tab. 5: Number of 700 kWth installations and saved carbon monetary value per percentage of ISTS penetration into considered energy mixes

Country	Number of installations	Saved Carbon monetary value [M€]
Greece	188	46,74
Germany	3343	831,02

5. Concluding remarks

While solar thermal technologies are widely used in domestic applications across Europe, solar heat for industrial processes is still a niche market. The key objective of this work was to quantify the untapped potential of solar thermal in industrial applications, and provide recommendations for the development of financial incentives for the promotion of the technology. For this purpose, the environmental performance of ISTSs was defined through the implementation of LCA.

The LCA results demonstrated that the life-cycle phases of the investigated solar thermal systems that are the most detrimental to the environment include the raw material extraction and system manufacturing phases, as well as the use phase. The raw material extraction and system manufacturing phases contributed more than 85% of the total impact in the categories of ozone and element depletion, and ecotoxicity to human health and marine and terrestrial environments. The use phase was found to be the main contributor to the depletion of fossil fuels and the creation of photochemical ozone impact categories, as a result of fossil fuel combustion in the auxiliary heating system for the generation of hot water. The implementation of a parametric assessment on the environmental performance of ISTSs for specific European geographical locations with diverse solar potential allowed the development of a 'life-cycle produced to consumed energy' ratio, which indicated that applications located at lower latitudes (in the Northern Hemisphere) can achieve greater life-cycle energy and carbon savings than ISTS applications located at higher latitudes.

Lower-latitude locations have higher solar potential, generating higher energy yields for the supply of hot process water, whereas the use of an auxiliary system is substantially reduced. In particular, large-scale ISTS applications in Athens were found to achieve energy savings of 75 GJ and carbon savings of 5 tonnes of CO_2 per kWth, while the respective values for Frankfurt aM were 44 GJ and 3 tonnes of CO_2 per kWth. The ratio can also be used to support decision-making by policy-makers throughout the process of renewable energy support scheme development. In particular, in the case of large countries or unions that extend through several climatic zones, the 'life-cycle produced to consumed energy' ratio can provide significant guidance in setting realistic incentives in relation to local available potential.

The parametric analysis also enabled the development of scenarios of ISTS penetration into the industrial sector in relation to the EU ETS, as well as definition of the carbon monetary value for the selected Member States.

Evaluation of the required capacity of large- scale ISTS applications to satisfy the desired percentage of national industrial demands for hot water is supported by taking into consideration the carbon monetary value and geographical location of the application. The findings of this work can be exploited by European policy-makers as a guideline for the development of national strategic plans and investment aids for the promotion of large-scale solar heat water generation applications for industrial processes.

6. References

Carlsson, B., Persson, H., Meir, M., Rekstad, J., 2014. A total cost perspective on use of polymeric materials in solar collectors–Importance of environmental performance on suitability. App. Energy, 125, 10-20.

Carnevale, E., Lombardi, L., Zanchi, L. 2014. Life Cycle Assessment of solar energy systems: Comparison of photovoltaic and water thermal heater at domestic scale. Energy, 77, 434-446.

Comodi, G., Bevilacqua, M., Caresana, F., Pelagalli, L., Venella, P., Paciarotti, C., 2014. LCA analysis of renewable domestic hot water systems with unglazed and glazed solar thermal panels. Energy Procedia, 61, 234-237.

Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC.

Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.

Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community.

European Solar Thermal Industry Federation (ESTIF), 2015. Solar Thermal Markets in Europe Trends and Market Statistics 2014. Last accessed 17 May 2017. Available from: http://www.estif.org/home/

Fokaides, P. A., Kylili, A., 2014. Towards grid parity in insular energy systems: The case of photovoltaics (PV) in Cyprus. Energy Policy, 65, 223-228.

Greening, B., Azapagic, A., 2014. Domestic solar thermal water heating: A sustainable option for the UK?. Renewable Energy, 63, 23-36.

Hang, Y., Qu, M., Zhao, F., 2012. Economic and environmental life cycle analysis of solar hot water systems in the United States. Energy and Build., 45, 181-188.

IEA (International Energy Agency) Solar Heating & Cooling Programme, 2016. Solar Heat Worldwide Markets and Contribution to the Energy Supply 2014. Last accessed 17 May 2017. Available from: www.iea-shc.org/

International Energy Agency (IEA) World Energy Balance, 2017. Last accessed 17 May 2017. Available from: http://www.iea.org/sankey/

Investing.com, Carbon Emissions Futures Historical Data Last accessed 17 May 2017. Available from: https://www.investing.com/commodities/carbon-emissions-historical-data

IRENA (International Renewable Energy Agency), 2014. REmap 2030: A Renewable Energy Roadmap, June 2014, Abu Dhabi. Last accessed 17 May 2017. Available from: http://www.irena.org/remap/IRENA_REmap_Report_June_2014.pdf

ISO (International Organization for Standardization), 2006. ISO 14040:2006. Environmental Management- Life Cycle Assessment- Principles and Framework.

ISO (International Organization for Standardization), 2006. ISO 14044:2006. Environmental Management- Life Cycle Assessment- Requirements and guidelines.

Johnsun Heaters Ltd. Personal Communication. December 2016.

Kalogirou, S. A., 2002. Parabolic trough collectors for industrial process heat in Cyprus. Energy, 27(9), 813-830.

Kalogirou, S. A., 2003. The potential of solar industrial process heat applications. Appl. Energy, 76(4), 337-361.

Kalogirou, S. A., 2004. Solar thermal collectors and applications. Prog. Energy Combust.Sci., 30(3), 231-295.

Kalogirou, S. A., 2013. Solar energy engineering: processes and systems. Academic Press.

Kalogirou, S. A., & Tripanagnostopoulos, Y., 2007. Industrial application of PV/T solar energy systems. Appl. Therm. Eng., 27(8), 1259-1270.

Karagiorgas, M., Botzios, A., Tsoutsos, T., 2001. Industrial solar thermal applications in Greece: economic evaluation, quality requirements and case studies. Renewable Sustainable Energy Rev., 5(2), 157-173.

Kulkarni, G. N., Kedare, S. B., Bandyopadhyay, S., 2007. Determination of design space and optimization of solar water heating systems. Sol. Energy, 81(8), 958-968.

Kulkarni, G. N., Kedare, S. B., Bandyopadhyay, S., 2008. Design of solar thermal systems utilizing pressurized hot water storage for industrial applications. Sol. Energy, 82(8), 686-699.

Kylili, A., Fokaides, P. A., 2015. Competitive auction mechanisms for the promotion renewable energy technologies: The case of the 50MW photovoltaics projects in Cyprus. Renewable Sustainable Energy Rev., 42, 226-233.

Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C., 2014. Life cycle analysis of a building-integrated solar thermal collector, based on embodied energy and embodied carbon methodologies. Energy Build., 84, 378-387.

Lamnatou, C., Notton, G., Chemisana, D., Cristofari, C., 2015. The environmental performance of a building-integrated solar thermal collector, based on multiple approaches and life-cycle impact assessment methodologies. Build. Environ., 87, 45-58.

Muneer, T., Maubleu, S., Asif, M., 2006. Prospects of solar water heating for textile industry in Pakistan. Renewable Sustainable Energy Rev., 10(1), 1-23.

Otanicar, T. P., Golden, J. S., 2009. Comparative environmental and economic analysis of conventional and nanofluid solar hot water technologies. Environ. Sci. Technol., 43(15), 6082-6087.

Pyrgou, A., Kylili, A., Fokaides, P. A., 2016. The future of the Feed-in Tariff (FiT) scheme in Europe: The case of photovoltaics. Energy Policy, 95, 94-102.

Schnitzer, H., Brunner, C., Gwehenberger, G., 2007. Minimizing greenhouse gas emissions through the application of solar thermal energy in industrial processes. J. Cleaner Prod., 15(13), 1271-1286.

Thinkstep GaBi. (2017). GaBi's website. Available from: http://www.gabi-software.com/international/index/

Valentin software (2017). T*SOL Dynamic thermal Simulation Program for Designing and Optimizing Solar Thermal Systems. Last accessed 17 May 2017. Available from: www.valentin-software.com/en

Zambrana-Vasquez, D., Aranda-Usón, A., Zabalza-Bribián, I., Janez, 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. Cleaner Prod., 88, 29-42.

Appendix: Nomenclature

Abbreviation	Description	Unit
ADPE	Abiotic Resource Depletion Potential for elements	[kg Sb- equiv.]
ADPF	Abiotic Resource Depletion Potential of Fossil Fuels	[MJ]
AP	Acidification Potential	[kg SO_2- equiv.]
CWHS	Conventional Water Heating Systems	-
EP	Eutrophication Potential	[kg phosphate- equiv.]
ESTIF	European Solar Thermal Industry Federation	-
EU ETS	European Emission Trading System	-
FAETP	Fresh-Water Aquatic Ecotoxicity Potential	[kg DCB- equiv.]
GHG	Greenhouse Gases	-
GWP	Global Warming Potential	[kg CO_2- equiv.]
HTP	Human Toxicity Potential	[kg DCB- equiv.]
IEA	International Energy Agency	-
ISTS	Industrial Solar Thermal Systems	-
LCA	Life Cycle Assessment	-
LCC	Life Cycle Costing	-
LCIA	Life Cycle Impact Assessment	-
LCI	Life Cycle Inventory	-
MAETP	Marine Aquatic Ecotoxicity Potential	[kg DCB- equiv.]
NAP	National Action Plan	-
ODP	Ozone Depletion Potential	[kg R11- equiv.]
POCP	Photochemical Oxidant Creation Potential	[kg ethene- equiv.]
RES	Renewable Energy Sources	-
TETP	Terrestric Ecotoxicity Potential	[kg DCB- equiv.]