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Life Cycle Assessment of a solar thermal system in Spain, eco-design alternatives and derived climate change scenarios at Spanish and Chinese National levels

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A R T I C L E I N F O

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A B S T R A C T

Solar thermal energy is considered a 'clean' form of energy; however, environmental impacts occur during its life-cycle. The present work compares the environmental performance of two scenarios: a solar thermal system for providing domestic hot water (DHW) used in conjunction with a traditional natural gas heating system, and the natural gas heating system on its own. Weak points are found and different eco-design scenarios are eval- uated in order to achieve a more circular economy. In addition, the authors explore what would be the national Greenhouse Gas emission reduction potential of a wider use of domestic solar hot water systems (DSHW) in China's and Spain's built environment. In this case, five displacement methods are suggested to show how the emissions reduction vary.

Through a review of the state of the art and a Life Cycle Assessment of a solar system the two scenarios are assessed. Some impact categories, such as global warming, suggest a markedly better performance of the solar system (-65%). However, weak points in the solar solution have been identified as there is an increase of impacts in cases such as acidification (+6%) and eutrophication (+61%), mostly due to the metals used. The compo- nents with higher environmental impact are the collector, the tank, and the copper tubes.

The reduction of national emissions by promoting DSHW depends on the actual displaced technology/ies. The consequences on national emissions reduction depending on these choices are assessed. The potential reduction of emissions, if 30% of the DHW were covered with solar sources, would be between 0.38% and 0.50% in the case of Spain and between 0.12% and 0.63% in China.

1. Introduction and background

Since the beginning of the industrial age, human populations have expanded and greatly increased access to natural resources. The ex- ponential rise in human population has been paralleled by increased agriculture, urbanization and energy consumption. In a little over than a century, humans have already consumed a large portion of the existing fossil fuels, which took millions of years to produce (Crutzen, 2002). From the 1970's, after the oil crisis, renewable energy technol- ogies have been developed in order to supplement, and possibly ulti- mately replace, oil and other fossil fuels as the main source of energy (Kamp, 2008; Schnitzer, Brunner, & Gwehenberger, 2007). These types of energy are produced in continuous and virtually inexhaustible ways, using energy sources such as: solar, wind, hydro, biomass, and geothermal (Dincer, 2010).

1.1. The European Union's energy characteristics

Since 2004, the EU-28's net imports of energy have been greater than its primary production (EUROSTAT, 2018). Regarding the fossil fuel sourced energy, according to the European Commission (EC) Green Paper published in 2002 (European Comission, 2002), the EU was largely and increasingly dependent on fossil energy imported from non- EU countries. In 2002, the EU was dependant on approximately: 76% for oil, 40% for natural gas, and 50% for coal. After 12 years, the energy import dependency increased, reaching up to the 87.7% for crude oil and the 70.4% for natural gas (EUROSTAT, 2018).

As it has been known for many years already (Smithers & Smit, 1997), this accelerated evolution is having important global effects beyond fossil fuels depletion per se, such as climate change induced by human-released greenhouse gases, which is causing negative impacts on society and the economy. Specifically, the building sector is re- sponsible for around one third of the final energy consumption and for around one third of the global CO_2 emissions (IEA, 2018; IEA, 2013).

Being aware of this situation, the European Commission set a challenge for the year 2020: all new buildings shall be nearly "zero- energy" buildings (European Parliament, 2010, 2012), i.e., they should produce as much energy as they consume during their operational stage. Additionally, scientists have argued that the definition should be extended to also include other stages of the life cycle of a building (Blengini & Di Carlo, 2010; Hernandez & Kenny, 2010; Kylili & Fokaides, 2015; Li, Yang, & Lam, 2013; Passer, Kreiner, & Maydl, 2012). Two possible approaches to increase sustainability by reducing energy consumption in buildings can be applied: active and passive systems. In a passive building, shell systems such as windows, walls, floors, and roofs are designed to increase the building insulation in order to reduce the energy demand in the use stage, conducting to a lower environmental impact of the building in a life cycle perspective (Passer et al., 2012; Schmidt, Jensen, Clausen, Kamstrup, & Postlethwaite, 2004). However, once a building has been constructed, it is difficult to reduce its energy demand, and active solutions are re- quired. These systems are designed to capture the sun's energy to convert it into heat or electricity and cover the building energy de- mand, like solar collectors do. Different alternatives may be used to accomplish this objective and a proper comparative assessment is needed before investment (Assiego De Larriva, Calleja Rodríguez, Cejudo López, Raugei, & Fullana I Palmer, 2014).

The European Commission recently issued the Circular Economy Package (European Commission, 2015) to boost global competitiveness, foster sustainable economic growth and generate new jobs. Within this global strategy, the sustainable use of resources is essential, and two energy strategies come to front: energy efficiency and renewable energy (JRC, 2015).

On average, the energy use inside a residential building attributed to the operational water heating accounts for 18–25% of the buildings total final energy (EuroACE, 2004; IDAE, 2014). Domestic Solar Water Heating (DSWH) is a well-proven technology used to reduce the non- renewable energy demand for providing operational DHW, and its potential to reduce domestic energy use is frequently acknowledged (Hernandez & Kenny, 2012).

1.2. The Popular Republic of China's energy characteristics

China's energy development strategy can be divided into three stages since the reform and opening of the Chinese economy. In the first stage, before 1990, China's government emphasized energy self-suffi- ciency by adopting policies such as reducing oil burning and replacing oil with coal. The leading position of coal was strengthened in China's energy supply system in this first stage. In the second stage, during the 90 s, heavy industry developed rapidly and the proportion of heavy industry exceeded 50% of China's total industrial output value. The third stage started with the 21st century, in which the central govern- ment emphasizes energy security to meet soaring demand, and pay close attention to energy-related environmental sustainability, such as lowering carbon emissions.

Nowadays, China still depends on fossil energy. In 2010, the total energy consumption was 9×10^{11} GJ, of which coal, oil, and natural gas accounted for 68%, 19%, and 4.4% respectively. New energy, which comprise hydropower, nuclear power, and wind power com- bined, accounted for 8.6% of the total energy consumption (NBS, 2010). According to China's Energy Development Strategic Action Plan (2014-2020), efforts should be made to optimize the energy mix by increasing the share of low-carbon energy (The State Council, 2014). The statistics newly released by British Petroleum (British Petroleum, 2018) show that China's natural gas consumption increased by 15% in 2017, compared with to 2016, and reached 31 billion m^3 (i.e., 6.6% of 2017 total energy consumption); while solar energy grew by an amazing 76%. By 2020, the share of natural gas will contribute to above 10% according to the planning of The State Council (2014).

According to the latest evaluation the China Association of Building Energy Efficiency (CABEE, 2016), the building sector consumed 20% of China's total energy, which is approximately 15% of the energy con- sumption by the global building sector, and this percentage is still growing (Xiao, Wei, & Wang, 2014). To curb this rising trend, Chinese government thus formulated a series of polices. The Ministry of Housing and Urban-Rural Development planned to cut 3.4×10^9 GJ of fossil- based energy use during the 12th five-year plan (2011–2015), and 26% of this reduction was achieved from the promotion of renewable energy uses (MOHURD, 2012). In 2017, MOHURD released the "Building En- ergy Conservation and Green Building Development Plan" to guide energy-saving actions during the 13th five-year period (2016–2020). The plan set the goal towards "ultra-low energy building systems" by using cleaner energy as a key avenue. As a major energy consumer of a building, water heating system is especially encouraged to shift to sustainable energy in China. Recently, MOHURD required to add solar systems to over 2 billion m^2 when buildings are newly developed (MOHURD, 2017).

1.3. DSHW LCA case studies

Life cycle assessment (LCA) and eco-design are comprehensive and integrated methodologies that allow acting in the early stages of the product-supply chain alongside the more traditional, technical, and economic criteria (Lagerstedt, Luttropp, & Lindfors, 2003). Moreover, LCA is considered as an appropriate tool to assess sustainability of products (Ness, Urbel-Piirsalu, Anderberg, & Olsson, 2007).

Product design is a critical determinant of a manufacturer's com- petitiveness. It has been claimed that as much as 70–80% of the costs of product development, manufacture, and use are determined during the initial design stages (Barton, Love, & Taylor, 2001). The earlier in the product design life cycle a design team considers environmental factors, the greater the potential for cost reduction, and also environmental benefits (Mascle & Zhao, 2008). In that sense, eco-design has been defined as "the systematic integration of environmental considerations into product and process design" (Canada, 2003) and its main ad- vantage is that these considerations could be taken into proper account in the early stages of the design process.

LCA allows the quantification of environmental impacts and the evaluation of the improvement options throughout the life cycle of a process, product or activity (Jacquemin, Pontalier, & Sablayrolles, 2012). These options could be applied in different stages of the life cycle: process selection, used materials, design, end of life disposal, and system optimization (Azapagic & Cliff, 1999). As detailed in the ISO standard 14,040 (ISO, 2006), LCA addresses the issue of quantifying environmental impacts (e.g., the use of resources and the environ- mental consequences of releases) throughout a product's life cycle from raw material acquisition, through production, use, end-of-life treat- ment, recycling and final disposal (i.e. cradle-to-grave), thereby avoiding burden shifting. These characteristics make LCA a relevant and holistic methodology that allows a correct eco-design of products (Byggeth & Hochschorner, 2006; Cerdan, Gazulla, Raugei, Martinez, & Fullana-i-Palmer, 2009). In spite of this, there are often hindrances in integrating eco-design into the practice of small and medium en- terprises (SMEs) (Fullana-i-Palmer, Mantoux, Milà i Canals, & Gazulla, 2005; Le Pochat, Bertoluci, & Froelich, 2007). With SMEs, it is essential to apply the so-called Life Cycle Management (LCM) principles (Fullana-i-Palmer et al., 2011), which aim at putting LCA into practice, especially the "Good Enough is Best" principle (Bala, Raugei, Benveniste, Gazulla, & Fullana-i-Palmer, 2010). This is an aim that has been pursued by the LCA community for many years, especially within SETAC Europe developments, where LCA and LCM were even seen so distanced as to call them "two planets" (Rebitzer, Fullana, Jolliet, & Klöpffer, 2001) or, more recently, "Ebony and Ivory" (Baitz et al., 2013).

A variety of eco-design strategies exists, including the reduction of the amount and diversity of materials used; the improvement of the energy efficiency during the use phase; or the design for recycling, among others. The use of these strategies will depend on the type of product or service or the objective of the company (Cerdan et al., 2009; Gazulla, Raugei, & Fullana-I-Palmer, 2010; Lück, 2012; Muñoz, Gazulla, Bala, Puig, & Fullana, 2009; Platcheck, Schaeffer, Kindlein, & Cândido, 2008). The application of these strategies may entail saving raw materials and energy, as well as reducing emissions and waste, leading to a cost reduction, and allowing for a more circular economy. In the case of solar thermal systems, LCA studies have pointed to the implementation of eco-design strategies mainly related to changes in materials and reductions in heat losses. Battisti and Corrado (2005) identified that, for a thermal collector with integrated water storage, most of the environmental impacts were associated to the production phase, specifically the tubes made of copper, leading to a replacement of this material with steel. Related to the use phase, the authors also proposed the use of an additional covering for the collector, a trans- parent insulating material (TIM) layer, in order to improve its perfor- mance for energy production. Also related with the covering, Chaurasia and Twidell (2001) proposed in their study the evaluation of the per- formance of an integrated collector with and without a TIM layer. In this case, the collector with TIM glazing was found to be more effective than the glass glazed collector by reducing the heat loss factor (UL).

Martinopoulos, Tsilingiridis, and Kyriakis, (2013) identified the environmental impacts from the use of different materials in domestic solar hot water systems (DSWH). The net environmental gain achieved by the use of DSWH is influenced, by up to 20%, by the materials and techniques used, among others. In that study, LCAs of a range of typical DSWH were performed. Their environmental impact, as well as the influence from the use of different materials or/and manufacturing techniques on their impact, was identified. As thermal efficiency differs from system to system, their environmental performance is influenced mainly by the conventional energy substituted and, to a lesser extent, by the materials used for their production. A study comparing unglazed and glazed solar thermal panels showed that the performed LCA, using Eco-indicator 99, resulted in 198 eco-points for the DSWH with tradi-steps with a low energy demand).

(Piroozfar, Pomponi, and Farr (2016) concluded that, amongst the five solar heater types considered, the one with electric backup ap- peared to be the environmentally preferable one. The study also stresses the need for a life cycle approach in order to reflect environmental impacts holistically and to facilitate better decision making.

Another LCA, carried out by Allen, Hammond, Harajli, McManus, and Winnett, (2010), for a solar hot water system, concluded that the production phase, especially due to the production of aluminium, is a high energy intensive one and produces most of the environmental impacts of the system. The adopted eco-design solution was an increase of the recycled aluminium percentage for the collector frame. The re- sults of the study showed around a 20% reduction in several environ- mental impact categories.

2. Aim of this work

Although solar energy is considered as a' clean' form of energy, environmental impacts occur during the manufacturing, transportation, use and final disposal of the solar systems, due to the consumption of resources and the emission of pollutants. The environmental con- sequences of these transactions include, among others, natural re- sources depletion, greenhouse gas emissions and acidification. Therefore, it is necessary to evaluate solar technologies accounting for both the direct and indirect environmental impacts caused by the DSHW systems over their whole life cycle (Martinopoulos et al., 2013). These products and systems have been investigated and continuously improved in recent years (Comodi et al., 2014; Martinopoulos et al., 2013; Piroozfar et al., 2016) but there is still margin for further im- provement. Some guidelines have been issued to assess the environ- mental impacts of building components from a life-cycle perspective (Lasvaux et al., 2014).

This paper has obtained information extracted from the RENIA project (RENIA, 2012), which aimed at helping Spanish manufacturers of solar (thermal and PV) systems to optimize their products at the design level (Cerdan et al., 2009), reducing their life-cycle environ- mental impact, as well as to develop Environmental Product Declara- tions (EPD) (EN 15804, 2008). Although common in other countries, Spain has very little experience in EPDs, with few other projects such as those described in (Benveniste et al., 2011; Gazulla, 2012; Passer et al., 2015). Within this framework, this paper focuses on solar thermal collec- tors and tries to identify their weak points (materials, processes, com- ponents) from a life cycle perspective and to generate guidelines on how to optimize these systems in order to reduce their environmental impact. A comparison between two systems for DHW generation is carried out in Section 3. The first system consists of a natural gas boiler (the most common source of DHW in Spain (Institute for Energy Diversification & Saving - IDAE, 2016)), while the second one adds a solar contribution to the gas boiler. Results are described in Section 4. A second exercise is also done in order to understand the potential reduction of emissions at a national level when ensuring a contribution of DSHW of at least 30% of the DHW demand. In this case, a life cycle perspective has not been taken into account because the Spanish na tional glazed panels and in 18 eco-points for the unglazed one. Overall, national emissions inventory does not consider scope 3 emissions. In- 93% of the impact of the traditional DSWH was due to panel production (Comodi et al., 2014).

Ardente, Beccali, Cellura, and Lo Brano, (2005) identified that the direct energy used during the production process and installation is only 5% of the overall energy consumption and that another 6% is consumed in transportation along the life cycle stages. The remaining percentage is employed for the production of raw materials, used as process inputs. These results show that the direct energy requirement is much less important than the indirect one (in fact, the production processes consist mainly in cutting, welding, bending and assembling stead, the exercise focuses on the displacement of technologies, when the share of a renewable technology in the mix is increased. This issue is explored, and different results are provided, in Section 5. Although, the life cycle perspective is not included in the characterisation factors, the authors believe that this exercise is a starting point for discussing about different displacement methods and their consequences. The aim is to obtain an estimate of the directly avoided emissions and to check the consequences of choosing one displacement method or another. If a life cycle perspective were adopted with regards to national emissions, these emissions would increase. Likewise, if, in the avoided emissions due to the use of solar thermal, the whole life cycle were accounted for, then the avoided emissions would be reduced due to the emissions generated along the life cycle of the solar thermal system which, as discussed in this article. However, national emissions inventories still only account for direct emissions. Therefore, these are the ones that will be considered for the analysis of emissions reduction in China and Spain. The eco-design measures suggested in the article would con- tribute to reducing the emissions from solar thermal systems in the indirect life cycle stages.

3. Life cycle assessment of two DHW alternatives

3.1. Product systems

This LCA is focused on a product designed and sold by the Termicol Company, which was a partner in the abovementioned RENIA project. This product is a forced circulation solar system used to produce Domestic Hot Water (DHW). The LCA has been performed in line with ISO 14,044 (2006). The study was performed using the LCA software GaBi and the Ecoinvent database as the main source of background data. More specifically, the Energy Systems sub-database (Dones et al., 2007) was widely used, from which the original model, named *Solar System flat plate collector for one-family house – Hot water,* was chosen and adapted to be as close as possible to the real system (Termicol, 2011). Table 1 shows the adaptation and the main characteristics of the system.

3.2. Goal and scope definition

The main objective of this LCA is to evaluate the environmental impact of a solar system with forced circulation, and to compare it with a traditional heating system that uses natural gas as its main energy source. The results of the study should allow the identification of weak points in the system and the proposal of several eco-design scenarios. A life cycle based eco-design scenario development of industrial systems allows companies to know their products and their potential improve- ment, giving them an advantage over their competitors and a robust way to communicate to customers in environmental terms.

The functional unit (FU) is defined as the production of 1 kW h of thermal energy to cover the DHW demand of a 6 persons house (the same as in the Ecoinvent database), located in Barcelona, Catalonia, Spain. There are two basic energy scenarios: in the first one, the use of solar energy is combined with an auxiliary heating system using natural gas to meet the demand; in the second one, a system that only uses natural gas to meet the entire demand is modelled. For both cases, the life span considered is 20 years. System boundaries are shown in Figs. 1 and 2, respectively.

3.3. Inventory analysis

In the Life Cycle Inventory (LCI) Analysis, data were listed for each of the components and stages for both systems (Figs. 1 and 2).

Due to the fact that the studied solar system includes an auxiliary heating system to meet the yearly demand of DHW, some calculations were done for the use stage in order to calculate how much of the total energy was covered by each source (solar and natural gas). Literature containing real data on use stage of solar systems is scarce. However, use and maintenance stages are relevant as they have great influence in the performance of the solar system (Hernandez & Kenny, 2012).

According to the regulation established in Spain (CTE, 2013), building engineers must consider that each residential building's user consumes approximately 40 L of DHW at 45 °C every day, which means that a household with, for instance, six inhabitants has a yearly demand of DHW of 3180 kW h (Table 2). To know how much of this demand can be covered by the solar system, also called the solar contribution, two basic parameters should be taken into account: the collector thermal efficiency F_R (U_L), related to the thermal losses (U_L); and the optical efficiency FR (τα), related to the light transmission capacity of the covering (τ) and the absorption capacity of the copper surface of the collector (α) (Duffie & Beckman, 2001). Producers of this type of sys- tems usually provide values for both of these parameters. For the as- sessed system, the thermal efficiency is 4.086 W/(m^2 K) and the optical efficiency is 0.77. Therefore, and also considering the tank capacity and the area of the collector (78.9 L/m^2), the solar system under study is able to cover 75.6% of the yearly demand of DHW. The auxiliary heating system that uses natural gas should cover the rest. Table 2 re- ports values for each month and for the yearly total.

3.4. Impact assessment

In order to describe the environmental impacts of the system throughout its life cycle, some categories were selected following the recommendations of the EN 15804 (2011), which contains the core rules for developing Product Category Rules (PCR) of construction products. The selected categories for emissions taken from the CML 2001 method, due to its problem-oriented perspective (Monteiro & Freire, 2012), are those included in the EN 15,804:

· Acidification Potential
· Eutrophication Potential
· Global Warming Potential
· Ozone Layer Depletion Potential
· Photochemical Ozone Creation Potential

Table 1
Adaptation and characteristics of the forced circulation system.
(Source: Dones et al., 2007; Termicol, 2011).

Characteristic	Termicol model	Ecoinvent model	Adaptation required
Collector area	3.8 m^2	4 m^2	Adapt to the real area
Absorption surface	Copper Selective	Copper Selective	–
Covering	Low iron glass (8 kg/m^2)	Low iron glass (9.12 kg/m^2)	Adapt the weight
Collector frame	Aluminium	Aluminium	–
Insulation material	Rockwool	Rockwool	–
Water tank	300 L	600 L	Adapt to real volume
Expansion vessel	18 L	25 L	–
Tubes primary circuit	Copper (3.24 kg/m^2)	Copper (2.82 kg/m^2)	Adapt to real weight
Tubes secondary circuit	Copper 7.13 kg	Copper 8 kg	Adapt to real weight
Auxiliary heating system	Natural gas boiler	No auxiliary system	Add an auxiliary system to the model
Thermal fluid	Propylene Glycol	Propylene Glycol	–
Circulation Pump	102W	102W	–
Electricity grid	Spain	Switzerland	Adapt to Spanish Mix
Life	20 years	25 years	Use 20 years as a reference

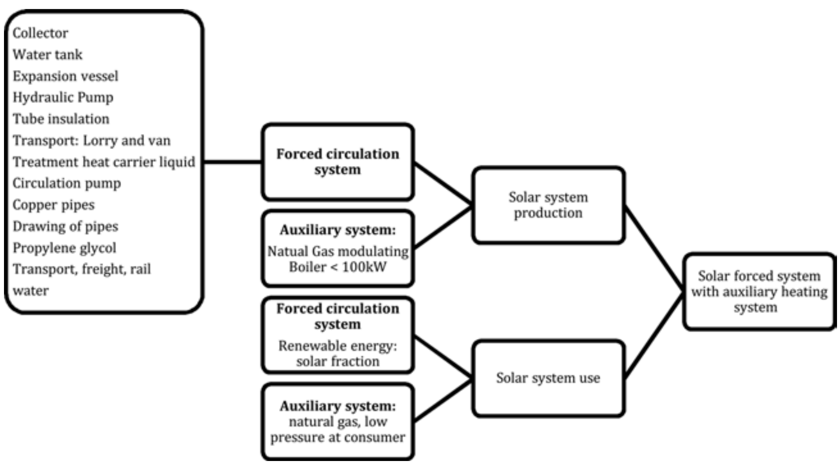

Fig. 1. System boundary for the solar system with forced circulation.

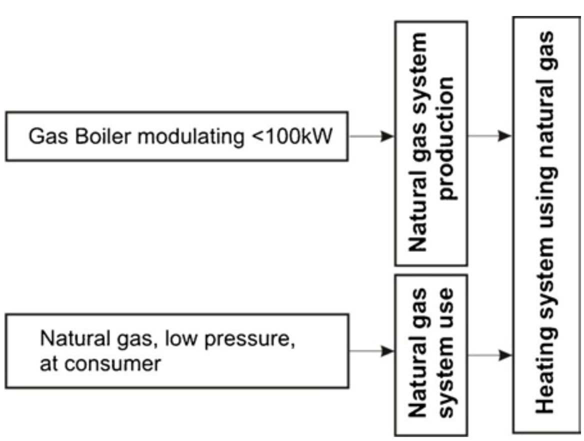

Fig. 2. System boundary for the natural gas heating system.

Table 2 Yearly DHW demand and solar contribution. (Source: CTE-2013).

Month	Temperature cold water (ºC)	DHW demand (kWh)	Solar contribution (kWh)	Solar contribution %
Jan	9	311	157.5	50.6
Feb	10	273	174.4	63.9
Mar	11	294	222.2	75.6
Apr	12	276	233.6	84.6
May	14	268	242.5	90.5
Jun	17	234	222.5	95.1
Jul	19	225	219.4	97.5
Aug	19	225	216.4	96.2
Sep	17	234	209.7	89.6
Oct	15	260	198.6	76.4
Nov	12	276	163.9	59.4
Dec	10	303	142.8	47.1
Total		3,181	2,403	75.6

In the case of the traditional heating system, the entire demand is covered with natural gas: 8781 m^3 of gas over the 20 years of life span.

The studied system is a high energy transformation product and, due to this fact, further impact metrics are used, related to the cumu- lative amounts of both non-renewable and total (renewable plus non- renewable) primary energy, which is directly and indirectly trans- formed over the system's lifetime. Both of these indicators, respectively named "non-renewable cumulative energy demand" (NR-CED) and "cumulative energy demand" (CED) are calculated including the in- direct energy demand for the provision of materials. In some older literature, NR-CED is sometimes also referred to as "gross energy re- quirement" (GER). This type of metric is a standard requirement by the EN (1580)4 (2011), and it has been widely used in the scientific lit- eratures for energy analyses (Gürzenich & Wagner, 2004; Slesser, 1974; Thiaux, Seigneurbieux, Multon, & Ben Ahmed, 2010) including pre- vious LCA studies co-performed by some of the authors (Ulgiati, Raugei, & Bargigli, 2006; Puig, Fullana-i-Palmer, Baquero, Riba, & Bala, 2013; Raugei, Bargigli, & Ulgiati, 2007; Ulgiati et al., 2011), in spite of not being a standard LCA metric.

4. Results and discussion

4.1. Environmental profile of the system

Table 3 reports the results for the emission-related categories de- scribed above and shows the percentage of relative change that the solar system produces when it is compared with a traditional natural gas heating system. The comparison between the two systems can also be seen in Table 4, where the cumulative primary energy demand is listed.

When the solar system is compared with a traditional system that uses natural gas for DHW production, a substantially environmental improvement is obtained due to the reduction of the Global Warming Potential (-65% in Table 3). This is often identified as one of the most relevant environmental indicators nowadays. This result is directly re- lated to the use of non-renewable primary energy (primary energy from non-renewable resources, Table 4), of which the solar system uses 64% less than the natural gas system (and, correspondingly, as expected, much more renewable energy). Improvements can also be seen in other impact categories of high relevance such as ozone layer depletion (-69%) and photochemical ozone formation (-41%).

Table 3
Comparison of environment impacts from natural gas system and solar system by life-cycle assessment.

Category	Unit	Natural gas system	Solar system	Relative change
Acidification	kg SO_2	2.35E-04	2.50E-04	+6.2%
Eutrophication	kg PO_4^{3-}	2.48E-05	4.00E-05	+61%
Global Warming	kg CO_2	2.64E-01	9.24E-02	−65%
Ozone Layer Depletion	kg CFC11	4.07E-08	1.25E-08	−69%
Photochemical Ozone Formation	kg ethene	6.06E-05	3.60E-05	−41%

Table 4
Values for non-renewable cumulative energy demand (NR-CED) and cumulative energy demand (CED).

	Unit	Natural gas system	Solar system	Relative change
NR-CED	MJ	4.63	1.65	−64.00%
CED	MJ	4.65	5.30	+13.90%

Table 5
Components with high environmental impacts in the solar system.

Category	Unit	Collector	Water tank	Copper tubes
Acidification	kg SO_2	33.8%	25.0%	8.3%
Eutrophication	kg PO_4^{3-}	23.8%	28.2%	1.8%
Global Warming Potential	kg CO_2	9.5%	14.6%	0.3%
Ozone Layer Depletion	kg CFC11	5.9%	6.6%	0.2%
Photochemical Ozone Formation	kg Ethene	17.8%	24.6%	3.0%

Categories like acidification and eutrophication (especially the latter) are weak points of the environmental profile of the solar system throughout its life cycle, instead. These results can be associated with the intensive use of metals in the production phase, causing an increase in the environmental levels of acidic gases or phyto-nutrient discharges (such as nitrogen or phosphorus).

However, acidification and eutrophication are local categories that need a more detailed analysis due to their radii of emission. For in- stance, in the case of the natural gas system, most of the emissions that come from burning gas are produced in a smaller radius, focusing their impact on the local community. On the other hand, the emissions from the solar system are mostly due to the production of components and extraction of materials, activities which can be carried out in different locations and possibly far from each other, making the emissions more scattered. A full analysis of the above mentioned aspects is highly re- levant in the analysis of local impact categories, but falls outside the scope of the present paper.

After comparing both systems, and as a second step of the analysis, the solar system was disaggregated into its components (Fig. 1) in order to find the ones that contribute the most to each of the impact cate- gories. As a result of this disaggregation, the collector, the tank and the copper tubes of the secondary circuit were identified as the components with the highest environmental impact in the system (Table 5).

4.2. Potential system improvements: eco-design scenarios

Based on the detection of weak points in the analysed solar system and guided by the previously commented analyses in Section 2 (Methods), the following eco-design scenarios were established and evaluated:

(1) Production phase: replacement of copper tubes with galvanized steel tubes in the secondary circuit of the system.
(2) Use phase: replacement of the glass covering with a multi-wall polycarbonate covering.
(3) Production phase: increase of the percentage of secondary (re- cycled) aluminium for the collector frame.

The described changes do not affect the system durability or its need to any additional maintenance.

4.2.1. Eco-design scenario 1: galvanized steel tubes

The main objective of this material substitution is to reduce the impact within the acidification and eutrophication categories by using a material that is widely used in Spain for tube production (galvanized steel). The virtual change of material was carried out taking into the consideration of the dimensional and functional equivalence between tubes, changing from 7.14 kg of copper to 16.5 kg of galvanized steel. The use of galvanized steel would yield a reduction of 5.77% in the acidification category for the solar system (Table 6) and a small re- duction in the photochemical ozone formation potential, too. The re- duction of these impacts is a positive result that could help to improve the environmental profile of the solar system. The values for primary energy demand (Table 7) would increase by a small proportion, de- monstrating that the heavier steel tubes would be slightly more energy-intensive than the existing copper ones.

4.2.2. Eco-design scenario 2: polycarbonate covering

The main objective of changing the covering material from glass to a multi-wall polycarbonate layer is to reduce the thermal losses and, therefore, obtain an increased efficiency of the collector and a higher solar fraction using less natural gas as an auxiliary source for heating. Multi-wall polycarbonate is known as an excellent material for in- sulation and it has been used before in other solar collectors (Chaurasia & Twidell, 2001). The selected material is a 10 mm thick two-wall polycarbonate. As the new material implies a change in the collector efficiency, the new data has to be included in the calculation for the new solar fraction. This type of polycarbonate has an optical efficiency FR ($\tau\alpha$) of 0.69 (lower than that of glass) and a thermal efficiency F_R (U_L) of 3.2 W/(m^2K). These values mean that polycarbonate has a lower capacity to let light pass through the covering, but compensates for that with lower thermal losses, obtaining a new solar fraction of 76%, which can be considered a similar value to the one obtained with the glass cover.

The gain in solar fraction is minimal (0.4%), and this performance can also be observed in the results for the emissions and primary energy demand (Table 6 and Table 7).

4.2.3. *Eco-design scenario 3: recycled aluminium for the collector frame*

The aluminium used to produce the collector frame is initially a "wrought alloy" consisting of 90% virgin or primary and 10% sec- ondary (from new scrap) aluminium (Eco-invent Data Base v 2.2., 2009). The objective of this scenario is to use a smaller percentage of primary aluminium in order to reduce the environmental impact of the collector. In order to take this into account in the analysis, a new type of aluminium is selected from the database ("cast alloy"), which contains 20% of primary aluminium, 47% of secondary aluminium from new compositions, irrespective of the specific manufacturing process ("cast" vs. "wrought"), wrought alloys could conceivably also be produced starting with a higher percentage of secondary aluminium (albeit probably not at the same price point, because of higher scrap rejection ratios).

In the case of Spain, aluminium collection and recycling still has a very long way to go. Results from the use of more recycled aluminium show a reduction in all of the emission impact categories (Table 6), especially in the acidification potential, eutrophication and photo- chemical ozone formation, demonstrating that the use of recycled alu- minium results in less impact in terms of emissions. The use of primary non-renewable energy in this scenario would decrease by 2.2%, which is a positive result from less use of energy to extract and produce virgin aluminium (Table 7).

Table 6
Emission values for the eco-design scenarios.

Category	Unit	Original solar system	Steel tubes	Polycarbonate	Recycled aluminium
Acidification	kg SO_2	2.50E-04	−5.77%	+0.6%	−4.63%
Eutrophication	kg PO_4	4.00E-05	+0.51%	+0.8%	−3.50%
Global Warming	kg CO_2	9.24E-02	+0.83%	−1.5%	−2.67%
Ozone Layer Depletion	kg CFC_{11}	1.25E-08	+0.48%	+0.7%	−1.14%
Photochemical Ozone Formation	kg C_2H_6	3.60E-05	−0.91%	−0.8%	−3.60%

Table 7 Primary energy demand for the eco-design scenarios.

Category	Unit	Original solar system	Steel tubes	Polycarbonate	Recycled aluminium
Primary energy from renewable raw materials	MJ	3.65	0%	0%	−0.2%
Primary energy from resources	MJ	1.65	+0.9%	−0.9%	−2.2%

Table 8 Energy source and CO_2 emissions in Spain for DHW production. (Source: (Institute for Energy Diversification and Saving - IDAE, 2016)).

SPAIN	DHW 2011 [MWh]	% DHW 2011	DHW2015 [MWh]	% DHW 2015	CF [t CO_2/MWh]	Emissions [t CO_2]
Coal	0	0.0%	0	0.0%	0.317	0.00E+00
Propane	7.18E+06	18.9%	5.41E+06	17.7%	0.234	1.27E+06
Diesel	1.79E+06	4.7%	1.86E+06	6.1%	0.263	4.89E+05
Natural Gas	2.12E+07	55.7%	1.50E+07	49.1%	0.182	2.73E+06
Solar thermal	1.55E+06	4.1%	2.39E+06	7.8%	–	0.00E+00
Geothermal	3.49E+04	0.1%	3.49E+04	0.1%	–	0.00E+00
Charcoal	1.28E+05	0.3%	6.98E+04	0.2%	–	0.00E+00
Wood	5.94E+05	1.6%	6.05E+05	2.0%	–	0.00E+00
Pellet	0	0.0%	0	0.0%	–	0.00E+00
Other Biomass	0	0.0%	0	0.0%	–	0.00E+00
Electricity	5.58E+06	14.7%	5.24E+06	17.1%	0.267	1.40E+09
TOTAL	3.80E+07	100.0%	3.06E+07	100.0%	1.92E-01	5.88E+06

Table 9 Baseline scenario, hypothesis, and results on five methods for technology substitution.

		Spain
BASELINE	National Emissions [t CO_2]	3.29E+08
	Year Reference	2015
	Demand DHW [MWh]	3.06E+07
	Current Contribution DSHW [MWh]	2.39E+06
	Current Share DSHW [%]	7.8
	Current Mix DHW [t CO_2-eq/MWh]	1.92E-01
	Current Emissions [t CO_2-eq]	5.88E+06
HYPOTHESIS	Demand DHW	Constant
	Suggested Share DSHW [%]	30
	Suggested contribution DSHW [MWh]	9.19E+06
MIX Mth	Displaced Demand of DHW – mix [MWh]	6.80E+06
	Mix Displaced [t CO_2-eq/MWh]	1.92E-01
	Resulting Mix [t CO_2-eq/MWh]	1.92E-01
	Emissions Reduction [t CO2-eq]	1.31E+06
	% of National Emissions Reduction [%]	0.397
MOST USED.Mth	Displaced Demand – most used (Natural Gas) [MWh]	6.80E+06
	Mix Displaced [t CO_2-eq/MWh]	1.82E-01
	Resulting Mix [t CO_2-eq/MWh]	1.52E-01
	Emissions Reduction [t CO_2-eq]	1.24E+06
	% of National Emissions Reduction [%]	0.376
POSITIVE Mth	Displaced Demand – positive marginal mix [MWh]	6.80E+06
	Marginal Mix displaced [t CO_2-eq/MWh]	2.25E-01
	Resulting Mix [t CO_2-eq/MWh]	2.00E-02
	Emissions Reduction [t CO_2-eq]	1.53E+06
	% of National Emissions Reduction [%]	0.466
NEGATIVE Mth	Displaced Demand – negative marginal mix [MWh]	6.80E+06
	Marginal Mix displaced [t CO_2-eq/MWh]	2.55E-01
	Resulting Mix [t CO_2-eq/MWh]	1.49E-01
	Emissions Reduction [t CO_2-eq]	1.33E+06
	% of National Emissions Reduction [%]	0.403
POLLUTING Mth	Displaced Demand – most polluting [MWh]	6.80E+06
	Mix displaced DHW [t CO_2-eq/MWh]	2.42E-01
	Resulting Mix [t CO_2-eq/MWh]	1.38E-01
	Emissions Reduction [t CO_2-eq]	1.65E+06
	% of National Emissions Reduction [%]	0.500

5. National scenarios on addressing climate change

5.1. Climate change mitigation targets

The result of the COP21 held in Paris was the parties' commitment to establishing a global response to keep the global temperature in- crease below 2 °C above pre-industrial levels during this century. This idea was written in the Paris Agreement (PA) (UNFCCC, 2015), which Spain ratified on 22nd April 2016. During the COP 22, the parties worked on practical (working programme (UNFCCC, 2016a)) and fi- nancial (UNFCCC, 2016b) aspects on how to implement the PA. Al- though Spain has not submitted them yet, under the PA the different parties are invited to upload their Intended Nationally Determined Contributions (INDCs) in a clear, transparent and understandable manner. These data will define the amount of reduction in CO_2-eq emissions that the country is expected to contribute so as to achieve the global goal.

China became the world largest carbon emitter in the world from 2007, and is the world largest residential energy consumer (Nejat, Jomehzadeh, Taheri, Gohari, & Muhd, 2015). On June 30, 2015, China submitted its INDC to the UNFCCC for preparing the COP21. Based on China's national circumstances and development stage, the Chinese scrap and 33% secondary aluminium from old scrap. The typically lower tensile strength of all cast alloys is assumed not to be a problem for the collector frame. In addition, since the environmental profile of these aluminium alloys primarily reflect their primary/secondary government proposed several goals towards 2030, including achieving the peaking of carbon dioxide emissions; a reduction of carbon dioxide emissions per unit of GDP of 60–65% compared to 2005 levels; an in- crease in the share of non-fossil fuels in primary energy consumption up o around 20%; and an increase in the forest stock volume by around 4.5 billion cubic meters with respect to 2005 levels.

Table 10 Positive method marginal mix.

	DHW 2011 [MWh]	% DHW 2011	DHW 2015 [MWh]	% DHW 2015	2015-2011 [MWh]	% Marginal	CF [t CO_2/MWh]	Emissions [t CO_2]
Diesel	1.79E+06	5	1.86E+06	6	6.98E + 04	86	0.263	1.84E+04
Solar Thermal	1.55E+06	4	2.39E+06	8	8.38E+05	0	0	0.00E + 00
Wood	5.94E+05	2	6.05E+05	2	1.16E+04	14	0	0.00E + 00
TOTAL					8.15E+05		2.25E-01	1.84E+04

Table 11 Energy displaced by technology applying the negative method

	DHW 2015 [MWh]	% Marginal	Increase of each technology
Solar Thermal	–	–	+6.80E + 06 MWh
Propane	5.41E+06 MWh	−21	−1.44E + 06 MWh
Natural Gas	1.50E+07 MWh	−74	−5.04E + 06 MWh
Charcoal	6.98E+04 MWh	−1	−4.75E + 04 MWh
Electricity	5.24E+06 MWh	−4	−2.76E + 05 MWh

Table 13 Energy uses of China's DHW and equivalent carbon emissions..

China	DHW 2013 [MWh]	% DHW 2013	DHW 2015 [MWh]	% DHW 2015	CF [t CO_2/ MWh]	Emissions 2015 [t CO_2]
Electricity	2.14E+08	57.63	2.06E+08	51.3	0.9625	1.99E+08
Natural Gas	8.97E+07	24.14	1.23E+08	30.6	0.182	2.24E+07
Solar thermal	6.51E+07	17.52	6.13E+07	15.2	–	0.00E + 00
Other	2.60E+06	0.7	1.17E+07	2.9	0.9625	1.12E+07
TOTAL	3.72E+08	100.0	4.03E+08	100.0	5.77E-01	2.32E+08

Note: CF represents carbon emission categorization factor, and Other CF is as- sumed to be represented by electricity because of the dominant role of air heat pump

In the following sub-sections the potential reduction of national emissions in the event that an increase of the share of solar thermal generation for DHW generation is mandated by the national govern- ments is assessed. The amount of CO_2 emission reduction depends on the criteria chosen to replace current sources of DHW generation. In the case of a single installation described in Sections 3 and 4, the com- parison was based on the avoided emission of a natural gas boiler. The reason for this choice is that natural gas is the main source of DHW generation in Spain. However, when assessing a wider scope, such as the avoided emissions at a country level, it is considered that a broader view of the substituted technologies should be applied.

Thus, five methods for technology displacement are explored: (i) *mix,* the most probable technologies to be substituted by the new technology (Solar thermal) are proportional to the current mix for DHW generation; (ii) *most used,* the increase of the share of DSWH implies a reduction in the most used technology; (iii) *positive,* the increase of the share of DSWH implies a substitution of a marginal mix of those tech- nologies that have a positive growth trend (between 2011 and 2015);
(iv) *negative,* the increase of the share of DSWH implies a substitution of a marginal mix of those technologies that have a negative growth trend (between 2011 and 2015); and (v) *polluting*, the increase of the share of DSWH implies a r eduction in the most polluting technologies, de- pending on their characterization factor (CF).

5.2. Spanish national scenarios

The Spanish household system uses around 614,453 TJ/year (Institute for Energy Diversification & Saving - IDAE, 2016), of which approximately 19% is used for DHW generation. The energy sources and related CO_2 emissions for DHW generation in 2011 and 2015 can be found in Table 8.

Current Spanish legislation (CTE, 2013) states that at least 30% (and up to 70% depending on the climatic zone) of the DHW production in new construction must be sourced by solar thermal technology. Table 9 shows the hypotheses used and the resultant reduction of emissions which may happen at the national level, if the above mentioned 30% is applied to all residential buildings in the country, based on the five different methods (Mth).

The five methods suggested have been applied displacing, in all cases, 6.80E + 06 MWh of energy sourced by different technologies. This amount of energy has displaced: (i) *mix*: the 2015 mix of tech- nologies; (ii) *most used*: natural gas; (iii) *positive*: a mix of 86% diesel and 14% wood (Table 10) (although it has a positive trend, Solar Thermal technology in the marginal positive mix is not considered, as it makes no sense to consider that promoting more solar will lead to displacement of solar); (iv) *negative*: a mix of 74% natural gas, 21% propane, 4% electricity, and 1% charcoal (Table 11); and (v) *polluting*: all diesel, and 4.94E + 06 MWh of propane are substituted by Solar generation (Table 12).

Table 12 Energy displaced by technology, depending on its emissions generated per unit of energy.

	DHW 2015 [MWh]	CF [t CO_2/MWh]	Increase [MWh]	Remaining [MWh]	Remaining to be displaced
Solar Thermal	2.39E+06	–	+6.80E + 06	9.19E+06	6.80E+06 MWh
Diesel	1.86E+06	0.263	−1.86E+06	0.00E + 00	4.94E+06 MWh
Propane	5.41E + 06	0.234	−4.94E + 06	4.70E+05	0.00E+00 MWh

5.3. Chinese national scenarios

The residential sector accounted for approximate 25% of China's total CO_2 emission and reached up to 320 $MtCO_2$ in 2011 (Nejat et al., 2015). However, China lacks the statistical data related to DHW. This is the reason why data from Zheng et al. (2014) is taken. Zheng, through a household survey, obtained that DHW share was 14% of Chinese household energy consumption in 2013. These authors also defined the structure of Chinese DHW energy consumption mix as: 43% electricity, 31% natural gas, 25% solar and 1% other. Similarly, the DHW energy mix of China in 2015 was calculated based on a national DHW survey (People's Daily Online, 2016), showing that the DHW energy mix of Chinese household was composed of 38% electricity, 37% natural gas, 21% solar and 4% others. Based on the two surveys, the emissions, derived from the DHW energy mixes in 2013 and 2015, for the case of China were calculated and summarized in Table 13.

In contrast with the Spanish case, in China's scenario a mandatory target for the contribution of solar technology in DHW production does not exist. Therefore, the considered scenarios for the increase of the advantages and weak points when compared to a traditional (natural Chinese energy demand of the DHW production sourced by solar thermal technology are the same than the solar contribution target of the Spanish national scenario (30%). The hypotheses and results of the Chinese national scenario based on the five different methods are shown in Table 14.

In Table 14, for all cases, 5.95E + 07 MWh sourced by the different technologies are replaced by the same quantity of solar technology. This amount of energy has displaced: (i) *mix*: of the 2015 mix of technologies; (ii) *most used*: electricity; (iii) *positive*: a mix of 79% nat- ural gas and 21% other (Table 15); (iv) *negative*: electricity (the same as "most used"); (v) *polluting*: all natural gas substituted by solar generation.

Table 14 Baseline scenario, hypotheses, and results on five methods for technology substitution of China's DHW scenarios. China

BASELINE	National Emissions	9.10E + 09 t CO_2
	Year Reference	2015
	Demand DHW [MWh]	4.03E+08
	Current Contribution DSHW [MWh]	6.13E+07
	Current Share DSHW [%]	15.2
	Current Mix DHW [t CO_2-eq/MWh]	5.77E-01
	Current Emissions [t CO_2-eq]	2.32E+08
HYPOTHESIS	Demand DHW	Constant
	Suggested Share DSHW [%]	30%
	Suggested contribution DSHW [MWh]	1.21E+08
MIX Mth	Displaced Demand of DHW – mix [MWh]	5.95E + 07
	Mix displaced [t CO_2-eq/MWh]	5.77E-01
	Resulting Mix [t CO_2-eq/MWh]	5.77E-01
	Emissions Reduction [t CO_2-eq]	3.43E + 07
	% of National Emissions Reduction [%]	0.377
MOST USED Mth	Displaced demand – most used (Natural Gas) [MWh]	5.95E + 07
	Mix displaced [t CO_2-eq/MWh]	9.63E-01
	Resulting Mix [t CO_2-eq/MWh]	4.35E-01
	Emissions Reduction [t CO_2-eq]	5.73E + 07
	% of National Emissions Reduction [%]	0.629
POSITIVE Mth	Displaced Demand – positive marginal mix [MWh]	5.95E + 07
	Marginal Mix displaced [t CO_2-eq/MWh]	3.48E-01
	Resulting Mix [t CO_2-eq/MWh]	3.48E-01
	Emissions Reduction [t CO_2-eq]	2.07E + 07
	% of National Emissions Reduction [%]	0.227
NEGATIVE Mth	Displaced Demand – negative marginal mix [MWh]	5.95E + 07
	Marginal Mix displaced [t CO_2-eq/MWh]	9.63E-01
	Resulting Mix [t CO_2-eq/MWh]	4.35E-01
	Emissions Reduction [t CO_2-eq]	5.73E + 07
	% of National Emissions Reduction [%]	0.629
POLLUTING Mth	Displaced Demand – most polluting [MWh]	5.95E + 07
	Mix displaced DHW [t CO_2-eq/MWh]	1.82E-01
	Resulting Mix [t CO_2-eq/MWh]	5.50E-01
	Emissions Reduction [t CO_2-eq]	1.08E + 06
	% of National Emissions Reduction [%]	0.119

Note: China's national carbon emission is cited from IEA, 2018.

Table 15
Positive method marginal mix for China's scenarios.

	DHW 2013 [MWh]	% DHW 2013	DHW 2015 [MWh]	% DHW 2015	2015-2013 [MWh]	% Marginal	CF [t CO_2/MWh]	Emissions [t CO_2]
Natural gas	8.97E + 07	24.1	1.23E + 08	30.6	3.35E + 07	79	0.182	6.08E + 06
Other	5.94E + 05	0.7	6.05E + 05	2.9	9.07E + 06	21	0.9625	8.37E + 06
TOTAL					4.26E + 07		3.48E-01	1.48E + 07

6. Conclusions

Carrying out an LCA of a forced solar thermal system to provide DHW to a six-person house led to the identification of environmental advantages and weak points when compared to a traditional (natural gas) heating system. Whereas the solar system already showed an im- portant improvement in relevant global impact categories such as global warming, ozone depletion and formation of photochemical ozone, there is still room for improvement. Solar thermal technologies can count on another advantage, namely their high energy density (amount of energy generated per m² of occupied roof). On the other hand, their fundamental weak points are in the acidification and eu- trophication categories, in which impacts were shown to be higher than for the conventional systems. In particular, the water tank, the collector and the copper tubes of the secondary circuit were found to be the components with the largest environmental impact.

The analysis led to the proposal of several eco-design scenarios. Specifically, the change of material in the tubes of the secondary circuit from cooper to galvanized steel showed a relevant improvement, especially in the acidification category. The use of a higher percentage of recycled aluminium in the collector frame also produced improve- ments in all studied categories. Instead, replacing the cover glass in the collector with a polycarbonate cover produced an almost exact match for the solar fraction and also for the environmental impacts, and was therefore not found to be a particularly effective eco-design strategy.

The potential reduction of emissions for the Spanish context, taking into account the increase of use of solar thermal technologies, varies depending on the DHW generation technologies displaced. The dec- arbonization of the energy mix and the electrification of the heating technologies will probably lead to a reduction in the avoided impacts of DSHW. However, nowadays there is still a lack of DSHW. A potential shift to renewable technologies of 22.2% of the energy used in DHW is possible. This would imply a reduction in between 1.24E + 06 and 1.65E + 06 tonnes of CO_2-eq emitted per year, corresponding between 0.38% and 0.5% of the total (329 Mt) CO_2-eq emissions in Spain in 2015.

By replacing electricity and natural gas with solar thermal tech- nology for DHW in different Chinese national scenarios, between 0.119% and 0.629% of the Chinese total CO_2-eq emitted in 2015 can be reduced. Therefore, China has more progress to shift into solar DHW and contribute to global GHG mitigation.

Future research should focus on exploring the feasibility of produ- cing the systems derived from the suggested eco-design scenarios at an industrial (manufacture) level, and their affectations in the installation stage. In addition, consensus on which is the most appropriate dis- placement method should be found so as to allow policy makers to better predict the variation of emissions if a new policy is implemented.

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