Sustainability assessment of home-made solar cookers for use in developed countries

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Abstract

The sustainability benefits of using solar cookers in developing countries have been analysed widely in the literature. However, the sustainability potential of solar cookers in developed economies has not been explored yet, which is the topic of this paper. Three types of solar cooker – box, panel and parabolic – were built as part of this research, mostly using reused household materials. Their life cycle environmental and economic performance was analysed and compared to conventional microwaves. The results were first considered at the level of individual cookers and then scaled up to the levels of a city, region and country, considering a conservative (10%) uptake of solar cookers. The contribution of home-made solar cookers to a circular economy and their social sustainability were also analysed. Spain was used as an illustrative example to demonstrate the potential sustainability benefits of using solar cookers in developed countries. The results suggest that, in comparison with microwaves, they could reduce annual life cycle costs by up to 40% and environmental impacts by up to 65%. They could also avoid annual emissions of 42,600 t of CO_2 eq. and the consumption of 860 TJ of primary energy at the national level. Furthermore, household waste would be reduced by 4200 t/yr and the electricity consumption by 67 GWh/yr. If solar cookers were built entirely by reusing household materials, up to €23.2 million could be saved annually at the national level. Finally, the development of craft activities to build and repair the cookers can help people to engage socially and reduce stress, thus enhancing their social wellbeing. It can also increase people's awareness of a more sustainable use of resources. Therefore, home-made solar cookers represent a promising opportunity to motivate behavioural changes towards a circular economy and sustainability in developed countries.

1. Introduction and literature review

Solar cookers are simple devices that utilise solar energy for heating or cooking of food (SCI 2004). Their use has been promoted widely as a sustainable alternative to biomass and fossil fuels in developing countries (Cuce and Cuce 2013). Consequently, the literature on solar cookers has mainly focused on their use in such regions. Example studies include optimisation of their design and performance (Panwar et al. 2012, Sexena et al. 2012, Cuce and Cuce 2013), economic and environmental benefits (Tucker 1999, Toonen 2009, Andrianaivo and Ramasiarinoro 2014) and social acceptability (Pohekar and Ramachandran 2004, Wentzel and Pouris 2007, Otte 2014). However, little attention has been paid to the potential sustainability benefits that solar cookers might bring to developed countries. These could include reduced use of energy from fossil-fuels, lower environmental impacts and costs as well as various social benefits.

For example, households in the European Union (EU) consume 25% (402 Mtoe) of the final energy, cause 20% (846 Mt) of annual GHG emissions and produce 8% (209 Mt) of total waste in the EU (Eurostat 2016a,b,c). A significant share of these is due to the use of electrical appliances (Eurostat 2014, EEA 2015a, EEA 2015b), such as microwaves and ovens for cooking or heating food. This is despite the appliances becoming increasingly more energy-efficient, driven by regulation and technology advancements. However, the 'rebound effect' negates these improvements as consumers in developed economies tend to replace appliances before they fail due to fashion trends and falling prices (EEA 2014a). Consequently, generation of electrical and electronic waste (e-waste) is increasing substantially, which leads to loss of valuable resources. Taking microwaves as an example, Gallego-Schmid et al. (2017) demonstrated that these appliances have notable environmental impacts due to electricity consumption and e-waste generation. An estimated 133 million microwaves in use in the EU (Mudgal et al. 2011) consume annually 148 PJ of primary energy, leading to the emissions of 6.9 Mt of CO_2 eq.; 184 kt of e-waste is also generate each year from the discarded units (Gallego-Schmid et al. 2017). The annual costs associated with the use of microwaves are also significant, amounting to €2.1 billion at the EU level (Mudgal et al. 2011; Eurostat 2017). Consequently, using home-made solar cookers instead of microwaves where possible might lead to significant resource, environmental and cost savings. Thus, they would be suitable for use in developed countries where microwaves are widely used, as opposed to developing countries where they are still scarce. They can be used in both urban and rural areas, although greater benefits could be achieved in the former, due to the fast-growing urban population. Additionally, solar cookers are versatile and adaptable devices that can be built using a large variety of resources (SCI 2004, Cuce and Cuce 2013), including household materials that would otherwise be discarded as waste.

Thus, this paper analyses the potential sustainability benefits of using home-made solar cookers instead of microwaves in developed countries with suitable climatic conditions. Spain is used as an illustrative example, considering three types of home-made solar cooker built as part of this research: box, panel and parabolic. Firstly, the life cycle environmental and economic performance of each type of the solar cooker was quantified to compare them to microwaves and identify improvement opportunities. Secondly, the annual environmental and costs implications of using solar cookers were determined considering their different lifespans and use intensities. Finally, the results were scaled up to different geographical levels – city, region and country – to determine the sustainability implications of using solar cookers instead of microwaves, assuming a conservatively low uptake. Additionally, the circular economy and social benefits of solar cookers were considered, including how their home-made fabrication and use could enhance wellbeing and encourage more sustainable behaviours.

2. Methods

As indicated in Figure 1, the research methodology developed and applied in this work to assess the sustainability of home-made solar cookers comprised the following main steps:

1. eco-design and construction of three types of solar cookers;
2. experimental measurements of their performance in real conditions;
3. life cycle assessment (LCA) to estimate environmental impacts;
4. life cycle costing (LCC) to determine overall costs;
5. scenario analysis and comparison with microwaves; and
6. other considerations: contribution to a circular economy and identification of relevant social sustainability aspects.

These steps are described in turn in the next sections.

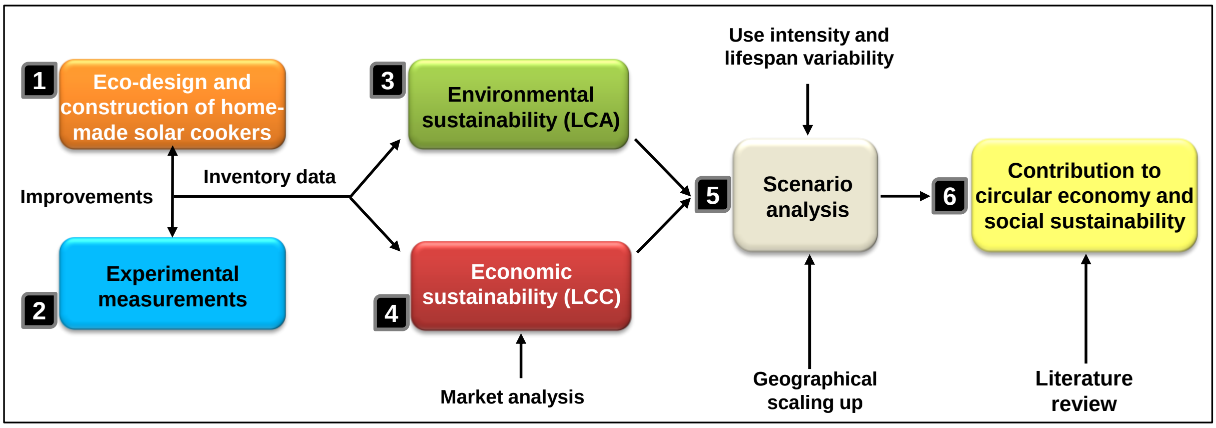


Figure 1 The methodology developed and applied to evaluate the sustainability of home-made solar cookers.

2.1. Eco-design and construction of solar cookers

The solar cookers considered in this work were designed by MSc students at the Institute of Environmental Science and Technology (ICTA) in the Universitat Autonoma de Barcelona (UAB), Spain. This activity was led by two authors of this paper (JMFM and JR). The students were asked to use eco-design principles to construct a solar cooker capable of heating their lunch outdoors. The following specifications were given to them for the development of the cookers:

- Concept: application of life cycle thinking to ensure eco-design criteria were applied in all life cycle stages of the cooker.
- Design: heating of one meal at a time; modular and foldable; reusable and easy to transport, use and repair, upgrade and repurpose.
- Materials: low environmental impact (mostly reused, recycled or recyclable) and low cost (if new materials were needed).
- Use performance: minimum temperature of 80 ºC. According to SCI (2010), food cooks at 82 ºC to 91 ºC. Thus, reaching 80 ºC would ensure that home-made solar cookers are able to heat food relatively quickly even in periods with low solar irradiation (e.g. autumn and winter).
- End-of-life waste: material recovery for reuse and upcycling.

The students were tasked with the development of three types of solar cookers: box, panel and parabolic. The study was repeated over five years with different cohorts of students, producing a wide variety of individual designs. Some of the examples are shown in Figure 2. An overview of the solar cookers is given below; for further details, see Section S1 and Figure S1 in Supporting Information (SI).

Box solar cookers (BSC): A BSC consists of an insulated cardboard or wood box with a transparent glass or plastic cover (window) on top to let in the sunlight and create the greenhouse effect. The use of reflective panels (shiny surfaces) helps to direct and concentrate the sunlight and increase heat generation in the box where the food container is placed. The inner part of the box (absorber tray) is dark (usually black) in order to maximise the sunlight absorption.


a) Box (shoe box) b) Panel (file folder) c) Parabolic (umbrella)

Figure 2 Examples of the solar cooker designs considered in the study (a) 30 cm width x 20 cm length x 60 cm height; b) 30 cm width x 40 cm length; c) 140 cm diameter).

Panel solar cookers (PSC): The design of PSCs is based on the use of reflective panels to direct sunlight to the entire surface of a dark-coloured food container, which is placed in a transparent heat-resistant plastic bag to generate the greenhouse effect (Cuce and Cuce 2013). However, the performance of this type of cooker depends highly on direct reflection of solar radiation and low wind. Consequently, they are not effective in cloudy or windy conditions (Cuce and Cuce 2013).

Parabolic solar cookers (PbSC): These cookers consist of a parabolic reflector that focuses a narrow beam of intense sunlight onto a food container. A metal stand is used to support the parabolic reflector and the food container, which is located at the focus point of the solar cooker. PbSCs can reach extremely high temperatures quickly. Thus, they have a superior performance over the other types of solar cooker.

The cookers were built by hand, mostly by reusing household materials. If new materials were needed, they were purchased from local stores. Examples of reused materials include shoe boxes, old umbrellas, glass panels from photo frames, aluminium food trays, fabric, newspapers and cork stoppers. Simple tools were used to construct the cookers, such as rulers, scissors and cutters.

2.2. Experimental measurements

Experimental measurements were carried out to determine how effective the solar cookers were in the use stage. This involved temperature measurements which took place in Barcelona on clear days in late autumn (November and early December) from 12:00 to 14:00. Thermal sensors were used to measure temperature variations every five minutes over a half hour period to determine if the designs could reach the minimum temperature required (80 ºC). The process was repeated twice to identify the best orientation of the cookers and improvements needed in the designs. As shown in Figures S2-S4 in the SI, all the cookers reached temperatures of around or above 80ºC, despite being used in winter when solar irradiance is low. Consequently, their use in periods with higher insolation would achieve higher temperatures in shorter periods of time.

In all cases, a dark metallic food container was required for the efficient performance of the solar cookers. In this study, a small bread loaf tin, commonly available in households, was used.

The experiments were carried out over five years, using consecutively improved solar cookers. These data were then averaged for each type of solar cooker and used to carry out the LCA, as described next.

It should be noted that any type of food (e.g. rice, chicken, potatoes, pasta, etc.) can be heated in solar cookers. Hence, the use of solar cookers is not limited to a specific type of food but rather to weather conditions, as described in section 2.5. However, some food types may require more time to be heated than others under the same conditions due to the nature of food. This is discussed further in section 3.4.

2.3. Life cycle assessment

The LCA study was performed following the methodological guidelines specified in the ISO 14040-44 (2006a,b) standards; this is detailed in the next sections.

2.3.1. Goal and scope of the study

The main goals of the LCA study were as follows:

i) to estimate the environmental impacts of solar cookers and identify improvement opportunities;
ii) to compare solar cookers against each other and with microwaves; and
iii) determine sustainability implications of using solar cookers with microwaves as back up.

In accordance with the above goals of the study, the following three functional units were defined:

i) "heating food with solar cookers once a day (lunchtime) over a period of eight months (240 days)": this functional unit was used to estimate the environmental impacts of the solar cookers and compare them against each other. The chosen period corresponds to the climatic conditions at the point of use (Barcelona), where on average 240 days per year are free from precipitation, fog, frost or storms (AEMET 2016). Different lifespans of the cookers were considered – one, three and eight months – to determine the corresponding variation in the results. This means that the number of cookers required over the period considered varied from eight for the shortest lifespan to one for the longest.
ii) "heating food in a single-use cycle": this functional unit was used for both the solar cookers and microwaves to enable their comparison. The impacts per single use were estimated taking into account the total number of uses of the cookers and microwaves (9600) over eight years (Mudgal et al. 2011). The shortest lifespan of solar cookers (one month, requiring eight solar cookers over the period of eight months) was assumed in this case to determine the minimum savings that could be achieved if they substituted microwaves. However, the effect on the variability on the solar cookers' lifespan is explored further as part of the sensitivity analysis in section 2.5.
iii) "heating food using solar cookers and microwaves as backup over one year": this functional unit was used to determine the sustainability implications of using solar cookers in combination with microwaves. The analysis was carried out at two levels: for individual solar cookers and for different geographical scales (city, region and country).

The system boundaries were defined from 'cradle to grave' (Figure 3), considering extraction and processing of raw materials (where relevant), product assembly, use, replacement and disposal. All relevant transport steps were also considered. At the end of their useful lifetime, the replaced cooker parts were assumed to be reused, incinerated with energy recovery or landfilled, as detailed in section 2.3.2. Different lifetimes of the cookers were considered, depending on the intensity of their use, as described in section 2.5.

For the microwaves, the system boundary was also from 'cradle to grave' (Figure 3), comprising extraction and processing of raw materials, microwave manufacture and use (electricity consumption), end-of-life waste management and all transportation steps. Detailed information on the life cycle of microwaves can be found in Gallego-Schmid et al. (2017).

2.3.2. Life cycle inventory

The bill of materials for the different types of solar cooker is presented in Table 1. These values represent the averages of the data collected over five years from the eco-design of solar cookers described in section 2.2. In total, 15 different designs were considered, five for each type of the solar cooker. The detailed data for each cooker design can be found in Tables S1-S3 in the SI.

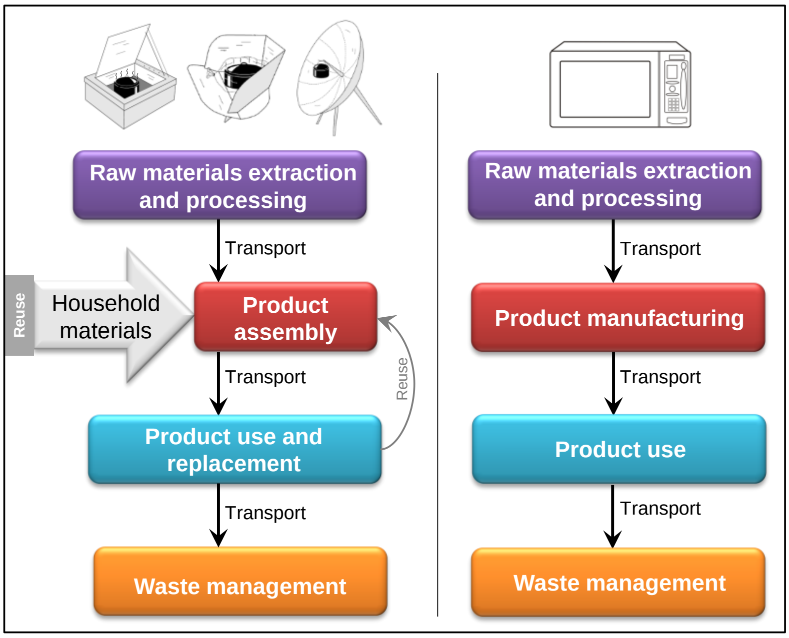


Figure 3 System boundaries and life cycle stages considered for the solar cookers and microwaves (Grey lines indicate that these material flows do not add any environmental burden and cost to the products, as described in section 2.3.2).

As can be seen in Table 1, the BSC is the heaviest cooker (1.56 kg), weighing 1.7 times more than the PbSC (915 g) and almost six times more than the PSC (265 g). The high material intensity of the box type is due to its design. Medium-size insulated wood or cardboard boxes and a number of cardboard panels were used to build BSC. These boxes and panels determine over 70% of the weight of the cooker, which increases further with the addition of glass panels to create the greenhouse effect and the use of aluminium sheets to reflect the sunlight into the interior of the box. All these materials together determine 91% of the weight of the BSC. Regarding the PbSC, the cardboard and aluminium sheets (including aluminium foil and glue) used to fabricate the reflection panels, represent almost 72% of the weight of the products. The rest of the weight is determined by materials used for the supporting structure of the reflection panels. Finally, the PSCs have the simplest and lighter designs. The use of cardboard alone determines 70% of their weight. The rest of the materials contribute between 1% (cotton thread) and 11% (metallic PVC).

It is worth noting that the total weight of the cookers is dominated by the reused rather than new materials, such as cardboard, wood, glass and aluminium. The reused materials were assumed not to have any environmental burdens as they were already used for other purposes and would have been discarded as waste. However, the new materials play an important role in the design of the cookers and most of them determine their performance. For instance, the use of black paint for heat absorption is essential for a proper performance of the BSC, whereas the use of aluminium foil and metallic reflection panels is crucial for an efficient use of PSCs. The latter also applies for PbSCs, where the panels should be supported by an effective structure. Likewise, ancillary materials, such as glue and tapes, are essential to bond the joints and preserve the cooker’s integrity.

No environmental burdens are generated in the use stage. However, handling, exposure to weather and water vapour generated during food heating can affect the durability of cookers over time. As a result, some parts or the whole cookers may need to be replaced. As the lifespans are uncertain, they have been considered as part of the scenario analysis described in section 2.5.

Table 1 Life cycle inventory and costs of home-made solar cookers.

Parts	Materials requirements	BSC[a]		PSC[a]		PbSC[a]	
		Mass (g)	Cost (€)	Mass (g)	Cost (€)	Mass (g)	Cost (€)
Box	Wood box (reused)	670	0	0	0	0	0
	Corrugated cardboard (reused)	469	0	185	0	392	0
Sun reflectors	Aluminium foil (new)	15	0.1	9	0.1	61	0.4
	Aluminium sheet/trays (reused)	115	0	2	0	140	0
	Metallic PVC[b] (new)	0	0	31	1.2	0	0
	PET film (new)	0	0	2	0.1	4	0.2
Heat concentrator	Glass panel (reused)	160	0	0	0	0	0
	HDPE film/bags (new)	9	0.4	7	0.3	6	0.3
	Polycarbonate sheet (new)	0	0	0	0	35	0.4
	Black paint (new)	8	0.2	0	0	0	0
	Black pasteboard (new)	0	0	12	0.1	0	0
	Black textile layer (reused)	10	0	0	0	0	0
Insulation	Newspaper (reused)	46	0	0	0	0	0
Fasteners and supports	Stainless steel (reused)	1	0	8	0	64	0
	Cotton threads (reused)	1	0	1	0	1	0
	Cork stoppers (reused)	10	0	1	0	0	0
	Wooden stick (reused)	0	0	1	0	63	0
	Polypropylene (reused)	0	0	0	0	7	0
	Nylon textile (reused)	0	0	0	0	54	0
Adhesives	Glue (new)	14	0.1	3	0.1	63	0.3
	Tape (new)	27	0.5	4	0.1	5	0.1
	Silicone (new)	2	0	0	0	0	0
	Velcro tape (new)	0	0	0	0	21	1.0
	Total	**1557**	**1.3**	**265**	**1.8**	**915**	**2.6**

[a] BSC: box solar cooker; PSC: panel solar cooker; PbSC: parabolic solar cooker.
[b] Reinforced with aluminium foil (10% wt).

No transport was considered for buying new materials as they were bought from local stores and transported to households by foot or bike. Once built, solar cookers were transported 25 km by train to the point of use (UAB campus) and the transportation impacts were allocated to the cookers by mass. Replaced materials were assumed to travel 50 km by road (16-32 t EURO 5 truck) from the point of use to municipal waste management facilities. Based on the end-of-life design requirements (see section 2.1), some reused materials were assumed to be reused for further solar cookers (wood boxes, glass panels, aluminium sheets, steel supports and fabrics). The new materials were assumed to be incinerated or landfilled as it would be difficult to separate them out for recycling (e.g. aluminium and glue, etc.). It was assumed that 17% of these would be incinerated with energy recovery (heat and electricity) and 83% landfilled with landfill gas utilisation. These values are based on the waste management practice in Spain, where 66% of waste is landfilled, 14% incinerated with energy recovery and 20% recycled (Eurostat 2016d). Given that the latter was not considered, the ratio of incinerated and landfilled waste was recalculated accordingly. The system was credited for energy recovery from incineration and landfill gas, displacing the equivalent amount of heat from natural gas and electricity from the Spanish grid.

The life cycle inventory (LCI) data for the microwaves were sourced from Gallego-Schmid et al. (2017). However, they were adapted to reflect the Spanish electricity mix; for the latter, see Table S4 in SI.

The background data were sourced from the Ecoinvent v2.2 database (SCLCI 2010) and any gaps supplemented by data from GaBi v6.1 (Thinkstep 2016). Specifically, the following data were sourced from the latter: carbon black and deionised water to produce black paint, aluminium foil and silicone sealing.

2.3.3. Life cycle environmental impact assessment

The CML 2001 method, last updated in 2016 (Guinée et al. 2001), was used to evaluate the environmental performance of home-made solar cookers and compare them to the microwaves. The following 11 environmental impacts were considered: abiotic depletion potential of elements ($ADP_{elements}$), abiotic depletion potential of fossil resources (ADP_{fossil}), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), freshwater aquatic ecotoxicity potential (FAETP), ozone depletion potential (ODP), photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP). The primary energy demand (PED) indicator was also estimated. GaBi software v7.2 (Thinkstep 2016) was used to model the system and estimate the impacts.

2.4. Life cycle costing

Only the life cycle costs of the new materials, purchased specifically for the solar cookers, were considered (see Table 1). The data were obtained through own market research and analysis, considering the average prices from at least four different retailers for each material. For end-of-life waste treatment, the cost of €45 per tonne of municipal solid waste was assumed (Fundación Vida Sostenible 2016).

The average cost of a conventional microwave was estimated at €63, based on the prices from over 40 different retailers and microwave brands sold in Spain. This price includes end-of-life waste management, due to the producer responsibility to collect and recycle a certain proportion of these appliances, which is effectively passed onto the consumer. For the use of microwaves, the cost of electricity in Spain was assumed at €0.237/kWh (Eurostat 2016e). Taking the lifespan of eight years and the total amount of electricity assumed over the lifetime, the cost per one use cycle of the microwave was assumed to be equal to €0.021. This includes €0.014 related to the electricity consumption (0.06 kWh/use) and €0.007 related to the cost of the microwave itself per single use.

2.5. Scenario analysis

In order to determine the magnitude and variability of the annual environmental and economic impacts associated with the solar cookers in comparison with the microwaves, different product lifespans and use intensities were considered through a scenario analysis. The variability in the use intensity is related to climatic conditions, whereas the variability in the lifespan is associated with the durability of the cookers. Furthermore, given that solar cookers can only be used in favourable climatic conditions, they cannot be utilised throughout the year and will need a backup appliance. Therefore, the scenario analysis also considers the implications of using solar cookers in combination with microwaves, assuming different climatic conditions and the resulting number of days per year that the cookers can be used, with microwaves being used for the rest of the time. The scenarios are summarised in Table 2 and described below.

The global average solar radiation in Barcelona is equivalent to 4.6 kWh/m^2day (AEMET 2012), whereas the standard insolation for solar cookers corresponds to 700-800 W/m^2 (Funk 2000; Schwarzer and Viera da Silva 2008). As mentioned earlier, the average meteorological data (1981-2010) indicate that there are 240 days per year free of rainfall, snow, storm, fog and frost (see Table S5 in SI). Consequently, solar cookers could be used to heat food during 66% of the year. For the rest of the year (125 days), other appliances, would be needed to heat the food, here assumed to be microwaves. However, this “Ideal” scenario reflects the best usage intensity for solar cookers. Consequently, a “Conservative” scenario considers that solar cookers would be used only in completely cloud-free weather, which accounts for 18% (65 days) of the year in Barcelona (AEMET 2016). Finally, an “Intermediate” scenario was also considered, assuming that solar cookers are used during 36% of the year (130 days). Microwave heating was assumed to supplement the use of solar cookers during the rest of year. Accordingly, the annual microwave usage requirements vary between these scenarios, as indicated in Table 2.

Table 2 Assumptions for the scenario analysis

Scenario	Sub-scenario	Cooking device	Use intensity (days)	Lifespan (months)	Product replacements (no.)
Ideal	A	Solar cookers	240	8	-
	B	Solar cookers	240	3	2.6
	C	Solar cookers	240	1	8.0
		Microwaves	125	96	-
Intermediate	A	Solar cookers	130	8	-
	B	Solar cookers	130	3	1.4
	C	Solar cookers	130	1	4.3
		Microwaves	235	96	-
Conservative	A	Solar cookers	65	8	-
	B	Solar cookers	65	3	-
	C	Solar cookers	65	1	2.2
		Microwaves	300	96	-

Three sub-scenarios were considered for each type of solar cookers with respect to their lifespan. In the best case (sub-scenarios A), it was assumed that well-designed cookers last eight months with no maintenance needed (Table 2). In the worst case (sub-scenarios C), the assumption was that poorly designed cookers would last one month only, after which the whole cooker would be replaced. In the intermediate case (sub-scenarios B), it was considered that solar cookers would be replaced every three months. However, it was assumed that some reused materials could be reused further in the development of new solar cookers. As mentioned earlier, these are wood boxes, glass panels, aluminium sheets, steel supports and fabrics.

2.6. Other considerations

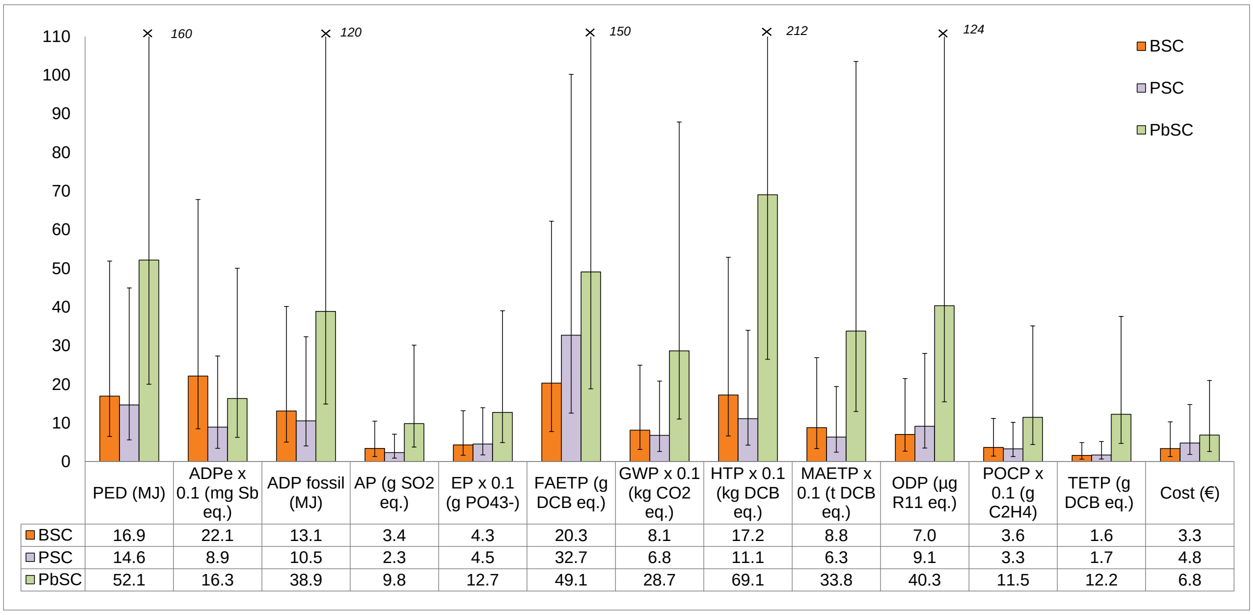
In addition to the environmental and economic sustainability evaluation, two further aspects were considered: i) the potential of solar cookers to contribute towards a circular economy; and ii) their implications for the social sustainability. The former was evaluated in relation to the improved resource efficiency (materials and energy) of solar cookers relative to the microwaves as well as their contribution to closing material loops and reducing waste generation. The social sustainability implications discussed include behavioural changes, community engagement and enhanced wellbeing. Potential barriers for their uptake were also considered.

3. Results and discussion

3.1. Environmental impacts and costs of solar cookers

The environmental impacts and costs the three types of solar cooker are compared in Figure 4 for the three lifespans considered, based on the functional unit “heating food with solar cookers once a day (lunchtime) over the period of eight months”.

As can be seen, the parabolic cooker is the least sustainable alternative for all impacts and lifespans, except ADP_e, and the costs. Its impacts are two (FAETP) to eight (TETP) times higher than those of the box and panel designs; it is also 1.4 and two times more expensive, respectively. However, the box cookers are the most material-intensive option, which is reflected in 1.4 and 2.5 times higher ADP_e than for the parabolic and panel alternatives, respectively. The panel cookers have the lowest impacts overall, except for FAETP, EP and ODP, for which box solar cookers are the best option. The box alternative is also the most cost effective.



	PED (MJ)	ADPe x 0.1 (mg Sb eq.)	ADP fossil (MJ)	AP (g SO2 eq.)	EP x 0.1 (g PO43-)	FAETP (g DCB eq.)	GWP x 0.1 (kg CO2 eq.)	HTP x 0.1 (kg DCB eq.)	MAETP x 0.1 (t DCB eq.)	ODP (μg R11 eq.)	POCP x 0.1 (g C2H4)	TETP (g DCB eq.)	Cost (€)
BSC	16.9	22.1	13.1	3.4	4.3	20.3	8.1	17.2	8.8	7.0	3.6	1.6	3.3
PSC	14.6	8.9	10.5	2.3	4.5	32.7	6.8	11.1	6.3	9.1	3.3	1.7	4.8
PbSC	52.1	16.3	38.9	9.8	12.7	49.1	28.7	69.1	33.8	40.3	11.5	12.2	6.8

Figure 4 Life cycle environmental impacts and costs of solar cookers

(All impacts and costs expressed per functional unit "use of cookers over the period of eight months". The minimum values in the error bars represent the lifespan of eight months (one cooker required); the maximum values the lifespan of one month (eight cookers needed) and the solid bars represent the values assuming the lifespan of three months (2.7 cookers required). The values in the table refer to the lifespan of three months. Some impacts have been scaled to fit; to obtain the original results, the values should be multiplied by the factors shown on the x-axis for relevant impacts. BSC: box solar cookers, PSC: panel solar cookers, PbSC: parabolic solar cookers. PED: primary energy demand, PED: primary energy demand, ADP_e: abiotic depletion potential of elements, ADP_f: abiotic depletion potential of fossil resources, AP: acidification potential, EP: eutrophication potential, GWP: global warming potential, HTP: human toxicity potential, MAETP: marine aquatic ecotoxicity potential, FAETP: freshwater aquatic ecotoxicity potential, ODP: ozone depletion potential, POCP: photochemical oxidants creation potential, TETP: terrestrial ecotoxicity potential. DCB – dichlorobenzene.)

It can also be seen in Figure 4 that the environmental impacts and costs of solar cookers with the short lifespan (one month) would increase by a factor of three relative to the medium lifetime (three months) due to the need to make three cookers over the period of eight months. However, the impacts would decrease by 2.6 times if solar cookers had a longer lifespan (eight months), as fewer solar cookers would be required over the period considered. As can be observed, these changes in the impacts are in direct proportion to the number cookers required over the period considered (eight months). This is because the reused materials do not contribute to the impacts and all the new materials have to be replaced when building new cookers as they are not reusable, hence determining the total impacts.

The contribution analysis in Figure 5 indicates that the raw materials, acquired specifically for making the cookers, determine between 70% (EP) to almost 100% (HTP) of the environmental impacts and costs across all the designs. This is despite their low contribution to the total weight of the cookers (see Table 1). A more detailed breakdown of their contribution to the impacts and costs can be seen in Figure 6. As indicated, the aluminium foil is the greatest contributor to most of the impacts for all three cooker types. This is followed by the tape and glue for the box solar cooker, black pasteboard and metallic PVC sheets for the panel solar cookers and the PC sheets, glue and Velcro tape for the parabolic. Silicone is the most significant material for the ADP$_\mathrm{e}$ of the box design, contributing 80% to the total. The tape and HDPE bag are the most expensive items for building these cookers, contributing around 70%, while for the panel option, it is the metallic PVC sheet (67%) and for the parabolic, the Velcro tape (~40%). Thus, the greatest reductions in the impacts and costs could be achieved if these materials were reused from other applications rather than acquired as new.

The only other life cycle stage that has a notable contribution to any of the categories considered is end-of-life waste management, which contributes ~10% to GWP, up to 18% to TETP and ~30% to EP. This stage also has a positive effect on ADP$_\mathrm{e}$, saving 40% of this impact due to the credits for the recovery of heat and electricity from incineration. There is also a positive effect on ADP$_\mathrm{f}$, AP, HTP, MAETP and PED, but the reductions are very small (0.1%-0.2%). Thus, active waste prevention through product light-weighting and reuse and recycling of materials is key to reducing the impacts of home-made solar cookers. Likewise, the design of cookers that are easy to disassemble into pure material streams (e.g. by avoiding the use of adhesives) would facilitate materials recyclability, leading to further reductions in the environmental impacts.

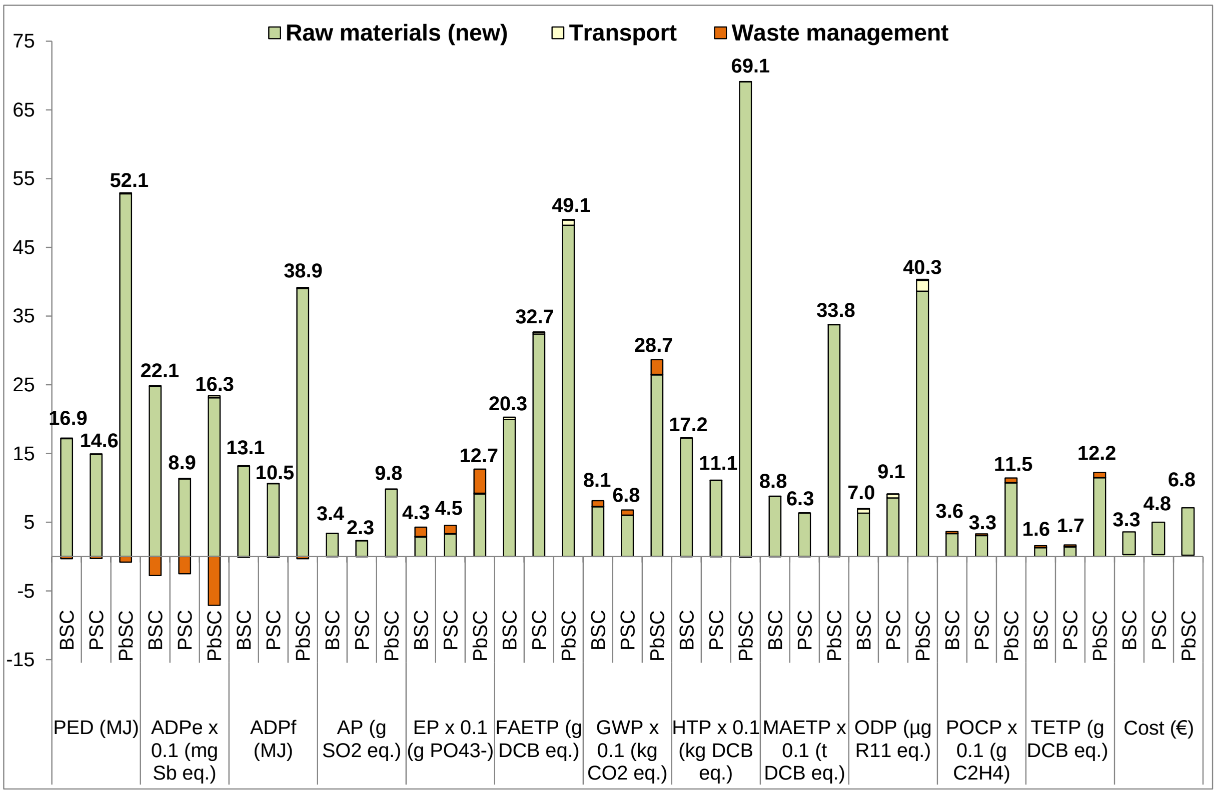


Figure 5 Contribution of different life cycle stages to the environmental impacts and costs of solar cookers

(All impacts and costs expressed per functional unit “use of cookers over the period of eight months”, assuming the lifespan of three months (2.7 cookers required). For the impacts nomenclature, see Figure 4. Some impacts have been scaled to fit; to obtain the original results, the values should be multiplied by the factors shown on the x-axis for relevant impacts.)

3.2. Comparison of solar cookers with microwaves

The solar cookers are compared to the microwaves in Table 3 for the functional unit “heating food in a single-use cycle”. As mentioned in section 2.3.1, solar cookers with the short lifespan (one month) were considered here to determine the minimum savings that could be achieved by using these devices instead of microwaves. The results indicate that the impacts of solar cookers are from 10% (GWP) to 59 times (FAETP) lower than for the microwaves. However, the use of parabolic cookers can increase ADP$_\mathrm{f}$ by 12% and HTP by almost three times compared to the use of microwaves. Likewise, the cost of heating food with solar cookers can be two to four times higher than using microwaves.

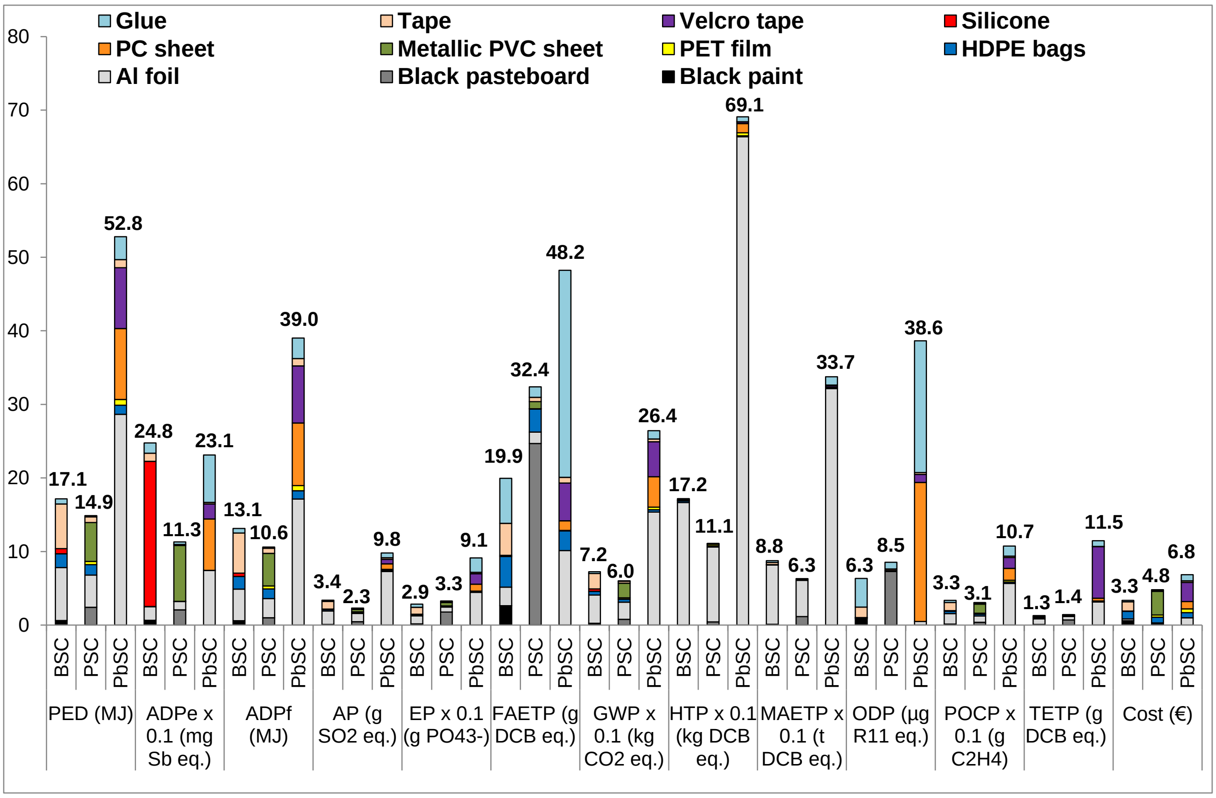


Figure 6 Contribution of new materials to the environmental and economic impacts of the solar cookers

(All impacts and costs expressed per functional unit “use of cookers over the period of eight months”, assuming the lifespan of three months (2.6 cookers required). Al: aluminium, HDPE: high density polyethylene, PC: polycarbonate, PET: polyethylene terephthalate, PVC: polyvinyl chloride. For the impacts nomenclature, see Figure 4. Some impacts have been scaled to fit; to obtain the original results, the values should be multiplied by the factors shown on the x-axis for relevant impacts.)

However, as mentioned in the introduction, microwaves can be discarded well before they reach the end of their expected lifespan of eight years, sometimes after five years, due to fashion or market trends (EEA 2014). Shorter-lived microwaves would then have even higher impacts and costs per use relative to the solar cookers. The impacts and costs of the latter could be reduced further by constructing them entirely from reused materials, as mentioned earlier. However, the lifespan and use intensity of solar cookers are constrained highly by the quality of materials and the design as well as the climatic conditions. An intense use of solar cookers could shorten their lifespan due to wear and tear. Likewise, they can only operate in favourable weather conditions and so need a backup appliance, such a microwave. These implications are explored in the scenario analysis in the next section, considering the use of cookers with microwaves as backup.

3.3. Scenario analysis: combined use of solar cookers and microwaves

3.3.1. Annual impacts and costs for single devices

Table 4 shows the annual environmental and cost savings for the combined use of a single panel solar cooker and a microwave compared to the use of a microwave alone in the baseline case. The results refer to the functional unit “heating food using solar cookers and microwaves as backup over one year”. The impacts and costs for the other two cookers can be found in Tables S6 and S7 in the SI.

Table 3 Life cycle environmental impacts and costs of microwaves and solar cookers per one use cycle

Indicators	Environmental impacts and costs per use			
	Microwave[a]	BSC[b]	PSC[b]	PbSC[b]
PED (kJ)	794.8	216.2	187.2	666.3
ADP_e (µg Sb eq.)	197.9	28.3	11.4	20.8
ADP_f (kJ)	441.7	167.2	134.6	496.4
AP (mg SO_2 eq.)	281.3	43.4	29.5	125.5
EP (mg PO_4^{3-})	88.1	5.5	5.8	16.3
FAETP (g DCB eq.)	15.3	0.3	0.4	0.6
GWP (g CO_2 eq.)	39.3	10.4	8.7	36.6
HTP (g DCB eq.)	29.7	22.0	14.2	88.2
MAETP (kg DCB eq.)	64.0	11.2	8.1	43.1
ODP (µg R11 eq.)	2.6	0.1	0.1	0.5
POCP (mg C_2H_4 eq.)	17.7	4.7	4.2	14.6
TETP (mg DCB eq.)	765.6	20.4	21.6	156.5
Cost (€)	0.021	0.043	0.061	0.087

[a] Lifespan of the microwave: eight years; 9600 use cycles. Data sourced from Gallego Schmid et al. (2017).

[b] Lifespan of solar cookers: one month. Eight cookers are required over the period of eight months.

The findings suggest that the combined use of the panel solar cooker and the microwave instead of using the microwave alone can reduce the annual environmental impacts by 9% (HTP) to 65% (ADP_e); the costs can be cut by 8% to 41%. This is mostly due to the electricity savings associated with using solar cookers instead of microwaves. However, depending on the scenario considered, the economic costs could be significantly greater than using microwaves only. For example, in sub-scenarios C the costs are 35%-128% higher than when only the microwaves are used. This is due to the need to build several cookers and particularly due to the costs of metallic PVC sheets, which make the panel cookers more expensive than the electricity used by microwaves. The costs are also higher for sub-scenario A and B in the Conservative scenario, again for the same reasons.

Table 4 Annual environmental and economic savings by the combined use of a panel solar cookers and a microwave compared to using microwaves only.

	Base-line[b]	Ideal scenario[c]			Intermediate scenario[d]			Conservative scenario[e]		
Indicators[a]		A[f]	B[f]	C[f]	A	B	C	A	B	C
PED (MJ)	8.1	-64%	-62%	-50%	-34%	-33%	-27%	-16%	-16%	-14%
ADP_e (mg Sb eq.)	72.2	-65%	-65%	-62%	-35%	-35%	-34%	-17%	-17%	-17%
ADP_f (MJ)	6.1	-63%	-61%	-46%	-33%	-33%	-25%	-15%	-15%	-12%
AP (g SO_2 eq.)	102.7	-65%	-64%	-59%	-35%	-34%	-32%	-17%	-17%	-16%
EP (g PO_4^{3-} eq.)	0.2	-65%	-65%	-61%	-35%	-35%	-33%	-17%	-17%	-17%
FAETP (g DCB eq.)	9.3	-66%	-65%	-64%	-35%	-35%	-35%	-18%	-18%	-17%
GWP (g CO_2 eq.)	393.0	-64%	-62%	-51%	-34%	-33%	-28%	-16%	-16%	-14%
HTP (g DCB eq.)	929.1	-62%	-56%	-34%	-32%	-30%	-19%	-14%	-14%	-9%
MAETP (t DCB eq.)	466.1	-65%	-63%	-57%	-35%	-34%	-31%	-17%	-17%	-16%
ODP (µg R11 eq.)	2.9	-65%	-65%	-63%	-35%	-35%	-34%	-17%	-17%	-17%
POCP (g C_2H_4 eq.)	6.5	-64%	-62%	-50%	-34%	-33%	-27%	-16%	-16%	-14%
TETP (g DCB eq.)	0.8	-66%	-65%	-64%	-35%	-35%	-35%	-18%	-18%	-17%
Cost (€)	1.6	-41%	-30%	+128%	-11%	-8%	+70%	+6%	+6%	+35%

[a] The impacts correspond to the functional unit "heating food using solar cookers and microwaves as backup over one year". For the acronyms, see Figure 4.

[b] Baseline: Microwave only, used once per day over 365 days. Lifespan: 8 years. LCA data: Gallego Schmid et al. (2017).

[c] Solar cooker used for 240 days of the year and microwave for the remaining 125 days.

[d] Solar cooker used for 130 days of the year and microwave for the remaining 235 days.

[e] Solar cooker used for 65 days of the year and microwave for the remaining 300 days.

[f] A: lifespan eight months; B: lifespan three months; C: lifespan one month.

The results for the box cooker (Table S6) indicate that similar environmental savings would be achieved as for the panel option, but it would have greater economic benefits because it is less expensive. However, the use of parabolic cookers would be less environmentally advantageous than the other two cookers (Table S7). It would also lead to a notable increase in the HTP (up to 130%) and costs (up to 211%), depending on the scenario considered. ADP_f would also increase by up to 8%. The increase in these two impacts is due to the greater consumption of aluminium foil and in the costs due to the Velcro tape.

Considering different lifespans, in sub-scenario C it was assumed that solar cookers last for one month, after which they are replaced by a new cooker. Consequently, two solar cookers should be built annually if they are used for 65 days annually (Conservative scenario). However, four and eight units would be required if solar cookers are used during 130 days and 240 days (Intermediate and Ideal scenarios), respectively. Thus, the input of new materials would increase, leading to an increase in the environmental impacts, which would be particularly noticeable for HTP if PbSC are used. The costs would also increase proportionally. As the number of cookers that would be needed is higher in the Ideal (use) scenario, the HTP and costs are higher for this than the other two scenarios. However, if the cookers' lifespan is longer, as in sub-scenarios A and B, the material inputs over time would be reduced. As a result, the impacts and costs of solar cookers would decrease independently of their use intensity over time.

Additionally, if solar cookers could be built entirely by reusing existing household materials rather than buying new, the maximum annual environmental and cost savings would be equivalent to the impacts and costs of using microwaves for 240 days (the maximum usage of solar cookers per year) which would now be avoided. Focusing on GWP as an example, the saving would correspond to 9.4 kg CO_2 eq. per year (39.3 g CO_2 eq. from microwaves x 240 uses/year). Thus, the use of cookers represents a promising alternative for reducing environmental impacts and costs of food heating, even if they need to be used in combination with microwaves as backup.

3.3.2. Impacts and costs at the city, regional and national levels

Scaling up the results discussed in the previous section to the city, regional and national levels yields the range of environmental and cost savings given in Table 5 for the panel solar cooker; the results of the other two types can be found in Tables S8 and S9 in the SI. The city of Barcelona, the region of Catalonia and the whole of Spain have been used to illustrate what can be achieved by using solar cookers in developed countries, both in cities and elsewhere. Taking a conservative approach, it was assumed that only 10% of the population use solar cookers at each of the geographical levels considered. This level of uptake reflects different constraining factors, including the availability of sunshine and the willingness of consumers to use solar cookers.

The results suggest that all the impacts would be reduced across the cookers and scenarios. For example, the use of panel solar cookers in Barcelona would reduce GHG emissions by 319-1471 t CO_2 eq. per year while at the level of whole Spain, the reductions would amount to 9235-42,559 t CO_2 eq./yr. The latter represents the saving of 64% compared to the use of microwaves only and it compensates annual GHG emissions of 21,290 households (EEA 2014b). The rest of the impacts would be reduced by 9% (HTP) to 65% (FAETP) at the national level. The use of box solar cookers would generate similar environmental savings, ranging from 5% (HTP) to 66% (FAETP); for the parabolic cookers, the savings would be between 1% (GWP) and 65% (FAETP). The exceptions to these trends are ADP_f and HTP for the parabolic cookers, which would increase by 2%-8% and 7%-130%, respectively. This is due to the high contribution of aluminium foil, as mentioned earlier.

Table 5 Annual environmental and economic savings by the combined use of solar cookers and microwaves at different geographical scales

Indicators[d]	Barcelona[a]		Catalonia[b]		Spain[c]	
	Min[e]	Max[e]	Min	Max	Min	Max
PED (TJ)	-6.3	-29.7	-29.7	-139.0	-183.4	-859.7
ADP_e (kg Sb eq.)	-1.9	-7.6	-9.1	-35.4	-56.3	-219.0
ADP_f (TJ)	-3.2	-16.4	-15.0	-76.6	-92.7	-473.5
AP (t SO_2 eq.)	-2.6	-10.7	-12.3	-50.0	-76.0	-309.3
EP (t PO_4^{3-} eq.)	-0.9	-3.4	-4.0	-15.7	-24.8	-97.4
FAETP (t DCB eq.)	-155.3	-587.7	-726.9	-2749.8	-4496.0	-17,008
GWP (t CO_2 eq.)	-319.1	-1470.5	-1493.0	-6880.9	-9234.6	-42,559
HTP (t DCB eq.)	-161.9	-1075.1	-757.8	-5030.6	-4686.8	-31,115
MAETP (kt DCB eq.)	-582.7	-2424.1	-2726.8	-11343	-16866	-70,157
ODP (g R11 eq.)	-25.5	-98.1	-119.4	-459.1	-738.3	-2839.7
POCP (t C_2H_4 eq.)	-0.1	-0.7	-0.7	-3.1	-4.1	-19.1
TETP (t DCB eq.)	-7.8	-29.4	-36.3	-137.5	-224.6	-850.3
Cost (million €)	-0.4	-0.5	+2.0	-2.4	+12.3	-14.6

[a] 160,456 users at 10% penetration of solar cookers into the market, based on the total population in Barcelona (Ajuntament de Barcelona 2017).

[b] 750,811 users at 10% penetration of solar cookers into the market, based on the total population in Catalonia (Generalitat de Catalunya 2017).

[c] 4,643,844 users at 10% penetration of solar cookers into the market, based on the total population in Spain (INE 2016).

[d] The impacts correspond to the functional unit "heating food using solar cookers and microwaves as backup over one year", assuming the total number of users as defined in footnotes a-c. For the acronyms, see Figure 4.

[e] Min: Conservative scenario (solar cookers used for 65 days, lifespan one month); Max: Ideal scenario (240 days, lifespan eight months).

The annual costs would also increase in the Conservative scenario, from €423,488 at the city level to €12.3 million for the whole of Spain. Likewise, they would also increase in the Intermediate and Ideal scenarios, by €0.8-24 m and €1.6-45 m, if the panel cookers with the short lifespan (one month) were used. On the other hand, up to €15 m would be saved if the Ideal scenario was realised using the panel cookers with long lifetimes (eight months). These economic savings would increase up to €17.2 m, if the box design was used instead (see Table S8 in the SI). Furthermore, the cost savings would increase to €23.2 million if the cookers were made entirely of reused household materials, while also reducing the environmental impacts. For GWP, this reduction would amount to around 43,932 t CO_2 eq./yr at the national level, a 34% reduction on the base case considered in the study.

3.4. Other considerations

3.4.1. Contribution of solar cookers to a circular economy

One of the main aims of a circular economy is to increase resource efficiency by reducing their use, keeping them in use as long as possible and closing material loops through reuse and recycling. In other words, the aim is to narrow, slow down and close resource loops (Bocken et al. 2016). Thus, home-made solar cookers have a potential to contribute towards this goal, as illustrated in Figure 7.

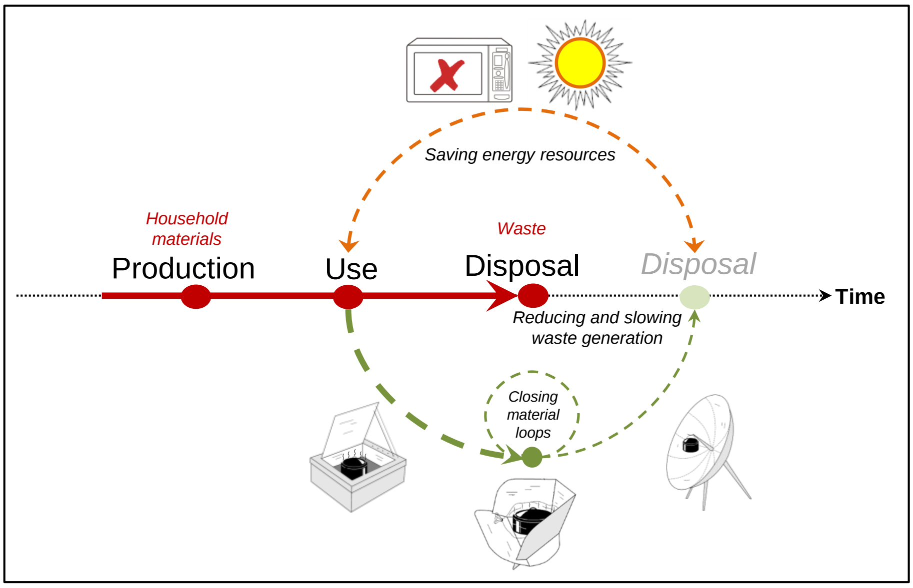


Figure 7 Contribution of solar cookers to a circular economy

Household materials will typically follow a linear life cycle, often being discarded shortly after their use. In developed countries, around 80% of commercial products are thrown away after a single use and 90% of the materials contained within goods become waste within six weeks of sale (Cohen-Rosenthal 2004). In Spain, for instance, over 72,000 tonnes of MSW are produced daily, of which 21% is cardboard and paper, 12% plastic, 8% glass and 4% metal (World Bank 2012). However, all of these can be reused as valuable materials in the construction of home-made solar cookers. Based on the assumptions in this study, this would reduce the amount of household waste by up to 4200 t/yr, which is equivalent to the annual waste generation by almost 9000 people (Eurostat 2016e). Thus, solar cookers can help to increase resource efficiency, close material loops and prevent waste generation, in congruence with the circular economy principles.

Nevertheless, solar cookers will eventually reach the end of their useful lifetime and become waste, which can be either reused again (in a new solar cooker or elsewhere) or recycled together with other MSW materials. However, generation of this waste would have been delayed in time, as shown in Figure 7.

In addition to the material resources, solar cookers also help to improve energy efficiency by substituting an equivalent amount of electricity used by microwaves. Assuming the electricity consumption by a microwave of 0.06 kWh per cycle and considering the Conservative and Ideal scenarios, the use of solar cookers can save annually between 18.1 and 66.9 GWh of electricity in Spain. These savings are equivalent to the electricity consumption by 60 to 223 million incandescent 60 W light bulbs used five hours per day.

Furthermore, solar cookers can be used as education devices to raise social awareness of the circular economy concept and stimulate simple but effective behavioural changes, as discussed next.

3.4.2. Social sustainability considerations

The uptake of home-made solar cookers will depend on many factors. Some of these include people’s awareness of environmental issues and their willingness to act to address them. According to the Eurobarometer survey (EC 2014), 85% of the EU citizens believe they can play a relevant role in protecting the environment because environmental issues affect directly their daily lives. Consequently, the adoption of environmentally-driven actions and behaviours is increasing, including waste separation for recycling, reducing energy and water consumption, purchase of local and ‘green’ products and/or reducing waste generation (EC 2014).

Importantly, the Europeans consider the sorting of waste for recycling and reducing home energy consumption to be among top environmental priorities (EC 2014). These considerations demonstrate a potential willingness to adopt sustainable practices, such as making and using solar cookers, which can contribute actively to reducing household waste and energy consumption. However, the annual cost of using home-made solar cookers in combination with microwaves could be higher than using microwaves only, depending on the product design (as discussed in section 3.3). Nevertheless, the above-mentioned Eurobarometer (EC 2014) suggests that a large majority (75%) of Europeans are also willing to pay a little more for ‘environmentally-friendly’ products. Most citizens also believe that the protection of the environment and the efficient use of resources can boost economic growth. Thus, if these claims are to be trusted, there is a potential for home-made solar cookers to be accepted by some proportion of the EU population.

Another important benefit of building and using solar cookers is related to the ‘do it yourself’ (DIY) character of these products, which can act as a wellbeing enhancer. Craft activities have been promoted as a way of dealing with mental and physical stress, stimulating creativity and facilitating social interactions (Corkhill et al. 2014). The development of DIY projects, including the construction of solar cookers, represents therefore an opportunity to encourage community bonding, which may be especially fruitful and rewarding in public organisations, such as universities, schools and social centres or even at the family level (Kuznetsov and Paulos 2010). This is aligned with the concept of “Living Labs”, user-centred spaces for the co-creation of innovative solutions by exchanging ideas, knowledge and real-life experiences (Garcia-Robles et al. 2015). Through Living Labs participants can propose, design and create their own solutions (e.g. products or services) to overcome social challenges, gaining a greater sense of empowerment and ownership (Eskelinen et al. 2015). Thus, Living Labs have gained popularity in many places worldwide. For instance, Universities, such as the UAB (ENoLL 2017) and the University of Manchester (UM 2017), have launched Living Lab initiatives to transform their campuses into a space for applied teaching and research on sustainability through the engagement of students, academics and professional-support staff (Evans et al. 2015). These Living Labs could be used, for example, as experimental spaces to co-create solutions for wider deployment of solar cookers. This could also lead to the creation of exchange platforms, such as Shrub (2017) or Repair Cafes (EMF 2016), to share household materials, expertise and skills for the fabrication, repair and upgrade of solar cookers. Indeed, citizens’ engagement to repair broken solar cookers would contribute to the so-called ‘product emotional durability and attachment’ (Bakker et al. 2014). These factors are essential in influencing consumers to use products for longer rather than replacing them quickly (van Nes and Cramer 2005).

Moreover, the use of solar cookers in organisations would reduce electricity consumption and the related costs. The resulting cost savings could be used to develop small grant schemes for the implementation of additional sustainability actions. Training courses and sustainability champions could further motivate and reinforce sustainable behaviours. Thus, one of the most relevant motivations for the construction and life cycle management of home-made solar cookers is ‘identity enhancement’, which is directly related to feelings of joy, empowerment or control, accomplishment, community engagement and customisation (Wolf and McQuitty 2011). As a result, home-made solar cookers have a great potential to increase social awareness and support behavioural changes towards sustainability.

Nevertheless, a potential barrier for the uptake of home-made solar cookers is the time needed to make them and to heat the food. Whereas microwaves are reliable and can be used at any time, solar cookers are weather-dependent. This restricts their use to a specific day time period when the sunshine is strongest. Additionally, heating food by solar cookers to a desired temperature may require 10 to 30 min, while a microwave takes just 2-3 min. Therefore, people need to plan ahead if they want to use solar cookers and this involves behavioural changes. Furthermore, solar cookers may need to be transported to the point of use every day or moved away after use to protect them from weather. This goes against the 'convenience lifestyle' most people in developed countries have grown accustomed to.

Another barrier for the uptake is the variability in their lifespan due to wear and tear. A short lifespan may require numerous repairs or frequent replacement of cookers. Nevertheless, using spare time to make and repair them could be appreciated by many people interested in DIY and craft activities.

4. Conclusions

This paper considered environmental, economic and social implications of using home-made solar cookers in developed countries instead of microwaves. The findings suggest that a high use intensity (240 days) of long-lived (eight months) solar cookers can reduce environmental impact by up to 65% and annual costs by up to 40% compared to using microwaves. On the other hand, the use of short-lived cookers (one month) may increase human toxicity, abiotic depletion of fossil fuels and the costs of food heating due to the need for additional new materials to repair and build new products. However, solar cookers made up entirely of reused materials would have negligible environmental impacts and costs.

The use of solar cookers in Spain could avoid the annual emission of 42,600 t of CO_2 eq. and reduce household waste by 4200 t. Household electricity consumption would decrease by 67 GWh and up to €23.2 million could be saved annually if solar cookers were built entirely from reused household materials. These benefits would increase further if more than the assumed 10% of the population adopted solar cookers.

Additionally, home-made solar cookers could drive behavioural changes towards a circular economy and social sustainability. The development of craft activities to build these products can help people to deal with stress, stimulating creativity and promoting positive social interactions. Thus, Living Labs and organisations promoting the construction of solar cookers may help to enhance social wellbeing and community engagement on sustainability issues, particularly in cities where communities are gradually being diminished. Likewise, social platforms (or local businesses) could be created to share household materials, knowledge and skills for building solar cookers. This could support the creation of new supply chains for reusing secondary household materials. It may also lead to physical or virtual meetings, where people could exchange innovative design approaches and life cycle management solutions. Consequently, home-made solar cookers represent a promising opportunity to facilitate the deployment of a circular economy and support sustainable development of communities in developed countries.

Future research activities should be focused on developing guidelines to ensure a systematic approach to eco-design and life cycle management of solar cookers as well as strategies to encourage their uptake. Evaluating the level of sustainability of solar cookers at the European level would also be valuable, together with research on the potential acceptability and uptake of these products. Comparison of solar cookers with other appliances for heating food could also be carried out, including the natural gas and electric stoves and ovens.

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Appendix A: Supporting Information

Supporting Information includes further details on the home-made solar cookers, experimental data on their performance, their composition and detailed results for the scenario analysis. The Spanish electricity mix and the meteorological data used in the analysis are also included.

List of acronyms

ADPe: Abiotic depletion potential of elements
ADPf: Abiotic depletion potential of fossil resources
AP: Acidification potential
BSC: Box solar cooker
DCB: Dichlorobenzene
FAETP: Freshwater aquatic ecotoxicity potential
GWP: Global warming potential
HDPE: High density polyethylene
HTP: Human toxicity potential
EP: Eutrophication potential
MATP: Marine aquatic ecotoxicity potential
MSW: Municipal solid waste
ODP: Ozone depletion potential
PbSC: Parabolic solar cooker
PC: Polycarbonate
PED: Primary energy demand
PET: Polyethylene terephthalate
POCP: Photochemical oxidants creation potential
PSC: Panel solar cooker
PVC: Polyvinyl chloride
TETP: Terrestrial ecotoxicity potential

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