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

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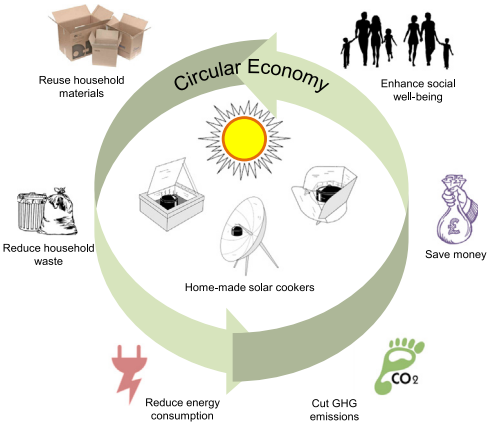
HIGHLIGHTS

- The benefits of using home-made solar cookers instead of microwaves are evaluated.
- GHG emissions and waste generation can be reduced by 42.6 kt and 4.2 kt annually.
- Around 67 GWh of electricity and €23.2 million can be saved each year.
- Social engagement in building and using solar cookers can enhance social wellbeing.
- They can motivate behavioural changes towards circular economy and sustainability.

GRAPHICAL ABSTRACT



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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, using mostly (>70%) 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 in substitution of microwaves. 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%, including greenhouse gas emissions. At the national level, 42,600 t of CO_2 eq. would be avoided annually while the consumption of primary energy would be reduced by 860 TJ. Furthermore, the electricity consumption would decrease by 67 GWh/yr and 4200 t/yr of household waste would be avoided. If solar cookers were built entirely by reusing household materials, up to €23.2 million could be saved per year. 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

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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, Saxena et al., 2011, 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 greenhouse gas emissions (GHG) emissions and produce 8% (209 Mt) of total waste in the EU (Eurostat, 2016a, 2016b, 2016c). A share of these, including >11% of household electricity consumption, 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.; 184,000 t of e-waste is also generated 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 could 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 environmental and economic performance of each type of the solar cooker was quantified and compared to microwaves. 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. Life cycle assessment (LCA) and life cycle costing (LCC) were used to quantify the environmental and economic sustainability of solar cookers. Due to a lack of data, it was not possible to carry out social LCA; instead, the social sustainability was evaluated at a qualitative level.

2. Methods

As indicated in Fig. 1, the research methodology developed and applied in this work 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.

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 °C. According to SCI (2010), food cooks at 82 °C to 91 °C. Thus, reaching 80 °C would ensure that home-made solar cookers are able to heat food 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 Fig. 2. An overview of the solar cookers is given below; for further details, see Section S1 and Fig. 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 such as aluminium foil) 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