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Life cycle assessment of a parabolic solar cooker and comparison with conventional cooking appliances

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Abstract:

Cooking is a basic need of humans that is fulfilled by a large variety of appliances and fuels. Some of them are responsible for large CO₂ emissions and environmental impacts, which might be reduced by using solar technologies. An analysis of the possibilities of reducing the ecological footprint and especially of climate impact mitigation through changing the cooking habits is necessary to inform the designers, producers and consumers of such appliances. To this aim, the environmental performances of conventional western means of cooking (induction hob, electric plate and gas hob) and of a solar concentration cooker were evaluated and compared using the Life Cycle Assessment (LCA) method, with the ReCiPe method more specifically. The life cycle inventory was built on real data collected for the selected devices. The actual and possible compositions (type and origin of materials like aluminium, recycled aluminium, wood) of the solar cooker were considered, with a total of 10 models. For conventional appliances, the energy consumption and efficiency were evaluated through experiments. Among the four types of appliances, the construction phase of the solar cooker has the highest impacts (for ReCiPe midpoint climate change indicator: 558 kgCO_{2eq} for the aluminium solar cooker against 463, 266 and 85 kgCO_{2eq} for the gas hob, the electric plate and the induction hob respectively). Nonetheless, due to the use phase, the impacts of conventional devices markedly rise (3278, 1169 and 760 kgCO_{2eq} for the gas hob, the electric plate and the induction hob respectively) and exceed those of the solar cookers irrespective of the construction material. The analysis was extended for different origins (and the related transportation activity) of the metallic components, and for different electricity emission factors in the use stage. Moreover, a combined use of one conventional and one solar cooker was investigated and the necessary utilization frequency of the solar cooker was determined to mitigate the climate footprint of the consumer. It was demonstrated that, e.g. the gas hob and electric appliances fed with a CO₂-intensive electricity can be advantageously replaced by currently available parabolic solar cookers, even for a moderate usage. With a low-carbon electricity mix, the advantage is preserved for an intensive use of the solar cooker and/or by decreasing the emissions related to the construction. The results show that this can be achieved by using recycled or Canadian aluminium and by using wood for the structure holding the reflector.

Key words:

Renewable energy; solar cooker; life cycle assessment

1. Introduction

Cooking is one of the primary activities of people around the world. Several techniques are used to cook using different energy sources *i.e.* electricity, solid fuel (wood, coal...), liquefied petroleum gas, natural gas, digested gas and solar irradiation (direct or indirect). For instance, in the U.S., the energy types used to cook are: electricity (61% of household stoves), followed by natural gas (33%) and liquefied petroleum gas (5%) [1]. This tendency is the one found in rich countries. Electricity can be a strong source of greenhouse gases (GHG) emissions depending on the energy mix. For instance, in the U.S, its production is primarily based on fossil fuels : in 2019, 62.5% of the electricity produced was based on fossil fuels like natural gas and coal [2]. In the low- and middle-income countries the main energy sources used to cook are solid fuels and liquefied petroleum gas. Hence, about 2.5 billion people worldwide use solid fuels such as wood, charcoal, crop residues or dung to cook, mostly with open fires [1]. It is well documented that open burning wood leads to health problems such as lung cancer or asthma, and environmental problems such as deforestation. One way to reduce the environmental and health impacts of cooking is to use solar concentrated energy. In the studies discussed in the literature review, only basic calculations were performed, neglecting the primary energy and resources required to build the solar cookers. This hypothesis is hard to justify since collecting solar energy requires large reflecting surfaces, often made of energy-intensive materials such as aluminium and/or glass. The potential interest of solar collectors for cooking has to be analysed using a more robust methodology and ideally, taking also into account environmental impacts other than CO₂ emissions.

In this context, the objective of the present work is to perform a comprehensive cradle to grave LCA of a solar cooker based on the structural characteristics of a commercial one (SK14, EG-Solar) and to compare its environmental performances with those of conventional cooking devices: an induction hob, a gas hob and an electric plate.

2. Literature review

Solar power has been studied for many applications: refrigeration and cooling [3]–[5], desalination [6], pasteurisation [7], distillation [8,9], hydrogen production [10]–[12], cremation [13] and cooking [14–24]. Edmonds [14] was able to cook vegetables, rice, meat and bread and to sterilize water, with an appropriate pan reaching 267°C. Mahavar *et al.* cooked 400 g of rice in 800 g of water and a pudding using a low-cost family box-type collector [15]. Mussard *et al.* boiled water and fried meat using a dish collector, a parabolic trough collector and a molten salt heat storage system [16]. The parabolic trough collector system showed competitive frying time in regards to the conventional appliances. Badran *et al.* boiled 7 L of water using a portable dish collector [17]. Saini *et al.* cooked food (rice and water or pulse and water) twice a day with a heat storage system and a parabolic trough collector using thermal oil as heat-carrying fluid [18]. Müller *et al.* showed that Scheffler collector-based solar ovens permit the baking of the weekly bread for 4 to 5 families in one day [19]. Schapers [20] reported on the utilisation of concentrated solar power to produce agave syrup in a Mexican woman cooperative using 6 Scheffler collectors. The production reached 250 L per sunny day, the same as using gas, and the saved money was used to pay the loan for the collectors.

The interest of solar technology is the absence of greenhouse gas or fine particle emissions during the use phase, thus reducing climate impact and health damages. For example, Herez *et al.* showed that, in Lebanon, using an exclusively solar cooker instead of a liquified petroleum

gas stove saves 60, 900, 4000 and 6000 kg of CO₂ per month in a home, a snack, a hotel and a restaurant, respectively [21]. Other studies have reported similar results : 200 to 300 kg of CO₂ are saved per year for each meter square of concentrated solar power (for any application) [22], about 425 kg of CO₂ could be saved per year for cooking cattle food in Rajasthan (India) [23] and potentially 33 million tons of CO₂ in Ethiopia if every Mirt fire and open fire were replaced. In the last case, the CO₂ and the non-CO₂ saved emissions (other greenhouse gas) would represent about 22% of the total CO_{2e} emissions of the country in 2010 [24].

However, life cycle assessment (LCA) of solar cookers are scarce. Mendoza *et al.* studied the sustainability of using a solar cooker and a microwave oven as a backup system [25]. The LCA analysis of the cookers was performed but the studied solar cookers were home-made using second-hand materials (cardboard, aluminium foil) and none of the concentrators was similar to a commercial one. Therefore, it does not represent typical solar cookers. Andrianaivo and Ramasiarino [26] showed that the use of solar cookers could reduce by 50% the ecological impact of a Malagasy family. However, in the LCA, it was assumed that all second-hand materials do not have any ecological weight or impact. Moreover, no details about the impacts of the manufacturing stage were provided and only the global warming potential (GWP) was assessed. To the best of our knowledge, the LCA of commercial parabolic solar cookers has never been performed as well as a detailed inventory of the manufacturing stage of the cooker.

3. Methods

This section describes the composition and fabrication process of the studied devices, and the energy consumption during the use stage. The solar cooker studied was a commercial single heating sport moveable parabolic cooker. In order to be consistent, the conventional devices were chosen to be single heating sport and moveable. Then, the modelling and hypotheses used to build the life cycle inventory are presented.

3.1. Description of the four cooking devices

3.1.1. Solar parabola cooker

The studied system is the EG-Solar SK14 model of a parabolic solar cooker [27]. All sunbeams incoming on the parabolic mirror are reflected toward the focal point, where the cooking pot is placed to be heated, as shown in Figure 1. The SK14 is composed of three

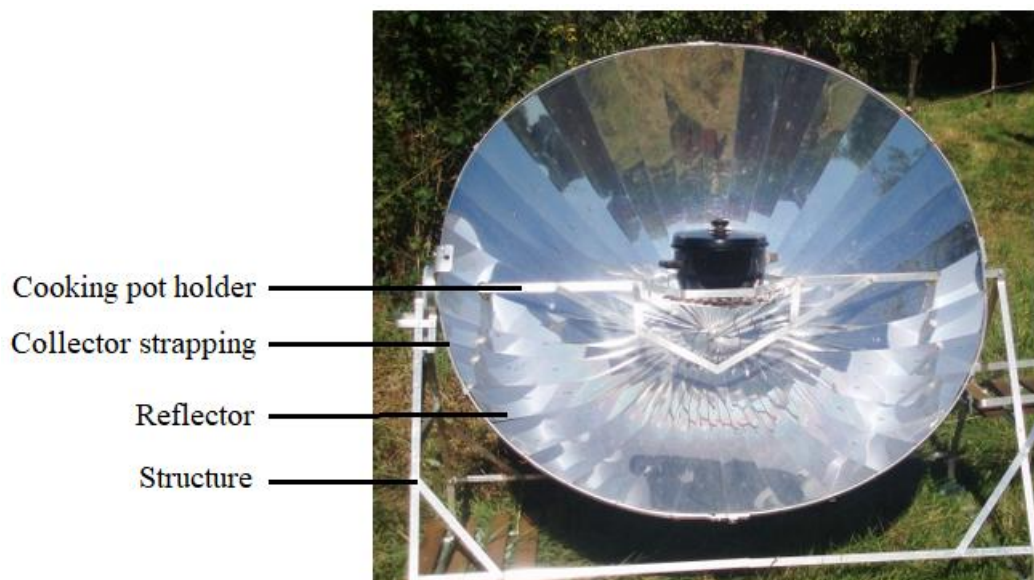


Figure 1: Parabolic solar cooker composition. Cooking pot holder: aluminium. Reflector: coated aluminium. Structure and collector strapping: aluminium or wood. The aluminium can be from China, from Canada or recycled.

parts: the structure, the collector and the cooking pot holder. The mobile structure allows manual sun tracking and is composed of aluminium profiles and stainless-steel screws and bolts. It supports the collector and the cooking pot. The collector is a parabolic mirror composed of 24 aluminium reflectors. Finally, the cooking pot holder allows to place the cooking pot at the focal point and is made of aluminium bars. Aluminium production is particularly energy-intensive and the environmental impacts of this industry highly depend on the electricity mix production. Therefore, a possible alternative material is envisaged here, namely the use of wood for the structure. In this variant, the collector and the cooking pot holder remain unchanged. Primary aluminium production is currently distributed around the world (North America, Europe, Asia...) but mainly originates from China. In 2020, 57.2% of aluminium was produced in China, the second producer being the Gulf Cooperation Council in the Middle East with 8.9% [28]. The International Aluminium Agency mentions that, in 2021, 35% of the aluminium produced came from recycling and, of the 35%, 41% comes from new scrap and 59% from old scrap [28, 29]. Furthermore, from an ecological point of view, the LCA ecoinvent database informs that the aluminium production with the lowest global warming potential is from Canada. Therefore, we decided to study cases with aluminium coming from China, from Canada or from recycling. The fabrication process of all parts of the solar cooker is detailed hereafter.

These data have been obtained from aluminium manufacturers, from the solar cooker manufacturer or – with respect to the wood structure – from private individuals who have fabricated them, including one of us (S.L.).

Reflector fabrication. The reflector is made out of triangular shaped aluminium sheets coated with a reflective layer deposited by a continuous air-vacuum-air physical vapour deposition process and with a protective nanocomposite layer deposited using a coil-coating process. Aluminium produced from bauxite and recycled aluminium are both produced in large ingots, which are then rolled to produce aluminium sheets. The sheets are coiled and sent to a first manufacturing site, where they are coated. The coated coils are cut into triangular pieces in a second manufacturing site, and then sent to the packing factory.

Structure fabrication. The manufacturing of the aluminium structure involves the following steps. First, the aluminium is produced in ingots which are then extruded to form a rectangular section aluminium profile. Then, those profiles are supplied to the packing factory – the same as for the reflector – and are manually bent if necessary. Finally, the profiles are assembled thanks to stainless steel screws and nuts to form the structure. The manufacturing process is the same whatever the origin of the aluminium used. The studied wood structure is made out of reclaimed wood of pallets (EPAL), which can be composed of over 25 different woods. Nonetheless, in Europe, the pallets are mainly made out of pine and fir wood for availability reasons. After being recovered, the wood is swan by hand and protected with linseed oil. Then, the wood parts are assembled using stainless-steel screws. The use of wood for the structure requires the use of additional screws to form the collector strapping. Indeed, whereas the aluminium structure is made of four quarter-circle bars, it is composed of 48 pieces when made of wood (see the picture in Supplementary information (SI) document, Figure A1).

Cooking pot holder manufacture. The cooking pot holder is composed of two parts. The first one is the pot support itself, made of a small circular aluminium bar bent several times. The second one is made of arched aluminium bars, similar to the ones used for the structure. This part links the pot support and the structure.

3.1.2. Induction hob

The studied induction hob (KP 1071, Severin) is a 2000 W single spot appliance made in China and composed of several parts: the power electronic board, a copper coil, a fan, a ceramic-glass and a housing (Figure 2). All the components of the electronic board are through hole or surface mounted on the board, which is fixed on the bottom of the polypropylene housing using stainless steel screws. The fan and the coil are also directly fixed to the housing using stainless steel screws. The upper part of the housing is composed of a glass-ceramics on which an acrylonitrile butadiene styrene joint is glued and both are encircled by a polypropylene strip. Finally, both parts of the housing are assembled together using stainless steel screws.



Figure 2: (left) Components inside the housing: electronic board (red), coil (blue), and fan (green). (right) Top part of the housing made of glass-ceramics.

3.1.3. Gas hob

For coherency with the induction hob, the gas hob (PRF315, Ribimex) is a China made 2900 W single burner gas stove including its hose. It comprises a knob to control the gas flow. The product can be assessed as two assemblies: the housing and the burner, as shown in Figure 3. The housing is composed of chromed steel walls with reinforcement in galvanised steel, a coated steel pot holder and the knob. The burner ensemble is composed of a hose in galvanised steel linked to a gas control assembly composed of steel, galvanised steel, brass and aluminium pieces, the burner itself being made of cast iron. Finally, a piezoelectric piece allows the gas ignition.



Figure 3: Gas hob studied: housing (left) and the burner assembly (right).

3.1.4. Electric plate

The studied electric plate (HPO15W, Proline) is made in China. It consists in a 1500 W single hob electric plate with a six-level thermostat. It uses an electric resistor to heat up a plate in direct contact with the cooking pot. It is composed of a housing, the wires and the hot plate assembly, as shown in Figure 4. The housing is composed of two parts (upper and lower) in coated steel with a rubber support. The hot plate ensemble is composed of a cast iron plate and a heating electric resistance covered with refractory cement. Then, an insulator layer and two housings made of galvanised steel and coated stainless steel complete the assembly.

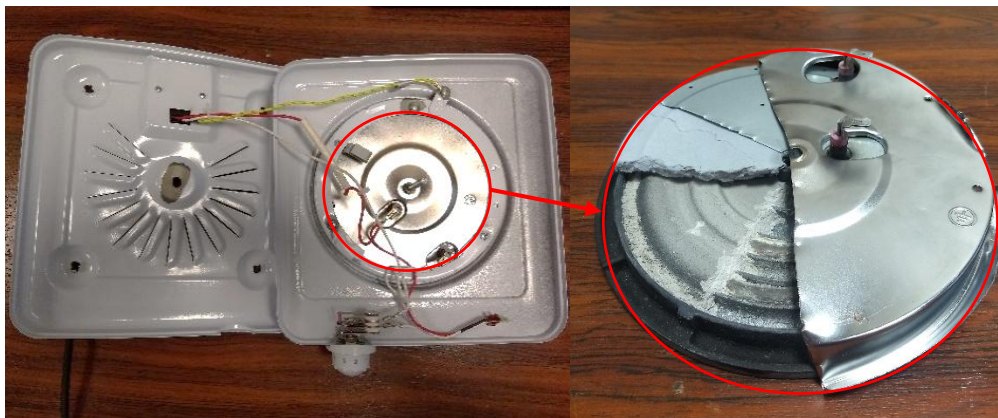


Figure 4: Opened electric plate (left) and cut view of the hot plate assembly (right)

3.2. Energy consumption during the use phase

Experiments were conducted to measure the energy required for heating a given quantity of water, i.e. 2L, in a cooking pot covered with lid. For the solar parabola cooker, since the sun irradiation has no ecological weight, such experiments were not necessary for the LCA.

However, experiments were realised to measure the temperature rising time, which is an important data for users. Results are available in SI B4.

For the induction hob and the electric plate, the energy required to heat the water was measured using a power meter (Polier, MM32LM) with a resolution of 10^{-2} kWh. Experiments with several thermostats were performed: for the electric plate, all of them were tested, while for the induction hob, 8 were tested (2, 4, 5, 6, 7, 8, 9 and 10 (maximum)). For the gas hob, experiments were realised on a standard household four-burner gas hob. This device was chosen because the gas consumption could be conveniently measured using the house gas meter (resolution of 10^{-5} Nm³) and because it permits to evaluate the influence of the burner diameter on energy efficiency. Experiments were performed on three of the burners, further referred as small, mean and large. For these experiments the knobs were set on four different positions, one allowing the smallest gas flow, one the largest and two intermediate positions.

For all heating experiments, the temperature was measured using two fibre optic temperature sensors (Reflex 4, Neoptix). One of the probes was placed *ca.* 1 cm below the water surface and the second one *ca.* 1 cm above the bottom of the cooking pot. The mean value was considered as being representative of the water temperature. The best adapted pot to each appliance was chosen.

The energy efficiency η was calculated from the consumed energy E_{exp} and from the theoretical value for the sensible heat E_{th} required to heat 2 L of water from 25°C to 90°C:

$$\eta = E_{\text{th}}/E_{\text{exp}} \quad \text{and} \quad E_{\text{th}} = m \cdot C_p \cdot \Delta T \quad (1)$$

where m is the mass of water, C_p the water mass calorific capacity and ΔT the temperature rise. In our case, the theoretical value is 0.151 kWh. For the gas, E_{exp} was calculated using the conversion factor from gas volume to energy given by the French natural gas distribution national operator (11.34 kWh.m⁻³). Latent heat of vaporization was neglected in Equations (1) because i) evaporation is expected to be small during the heating phase, ii) measurements were performed up to 90°C only and iii) all measurements were realised with a lid allowing evaporated water to condensate. Finally, in the energy inventory, the lowest E_{exp} value was chosen, and thus the highest efficiency for each appliance.

3.3. LCA application to the four devices

LCA is a widespread methodology for evaluating the environmental impacts of products, processes and services. The ISO 14040 standard [31] sets the principles of LCA application in four steps: 1) defining the goal and scope, 2) building the life cycle inventory (LCI), 3) performing the life cycle impact assessment (LCIA), 4) interpreting results and recommendations.

3.3.1. Goal and scope

The objective of this study is to evaluate the environmental impacts of a solar cooker from cradle to grave, *i.e.* over its entire life cycle, and to compare it with the cradle-to-grave LCA of alternative cooking appliances (induction hob, gas hob and electric plate – devices presented in section I.1). For the solar cooker, the influence of the material origin is analysed, by considering specificities of the producer countries (e.g. energy mix, metal production) and transportation. The functional unit is defined as “to produce, to use and to dispose a cooking

device with the following characteristics of the use stage: it heats 2L of water from 25°C to 90°C, using the most adapted cooking pot with a lid in each case, three times per day, every day, during 40 years”. System expansion was adopted as methodology. A duration of 40 years was chosen since it corresponds to the estimated life span of the aluminium structure of the solar cooker. The use phase takes place in France, as well as the device’s end of life. When possible, the chosen end-of-life treatment was recycling, the recovered materials avoiding new material manufacturing. The Umberto LCA+ software was used to perform the LCA with ecoinvent 3.8 and 2.2 databases for the background processes. Most of the equivalence come from the newest version, but some activities were available only in the old version hence the use of the 2.2 version. The inventory data were used with the cut-off allocation, as recommended in ecoinvent database.

3.3.2. Life cycle inventory

One specimen of each of the four devices was dismantled and the components weighted. Information about the supply chain and the component fabrication process were collected via surveys addressed to industrials and, for the wood solar cooker, to private individuals who crafted their own wood structure. The life cycle inventory with ecoinvent equivalences of the solar cookers, the induction hob, the gas hob and the electric plate are respectively presented Table 1, Table 2, Table 3 and Table 4.

Table 1: Complete life cycle inventory of the parabolas studied, and ecoinvent database equivalence

Device	Component	Quantity	Process	Ecoinvent activity ¹	Type	Area ²	Comment ²	
Solar cooker	Structure	8.25 kg	Aluminium production	Aluminium production, primary, ingot	Result	CN, CA		
			Rods production	Section bar extrusion, aluminium	Unit	RoW	With CA or CN electricity	
	Pot holder	2.75 kg	Aluminium production	Aluminium production, primary, ingot	Result	CN, CA		
			Rods production	Section bar extrusion, aluminium	Unit	RoW	With CA or CN electricity	
	Reflectors	10.80 kg	Aluminium production	Aluminium production, primary, ingot	Result	CN, CA		
			Sheet production	Sheet rolling, aluminium	Unit	RoW	With CA or CN electricity	
			Anodising, aluminium sheet		Result	RER		
	Additional raw materials	Depend on the quantity recycled (35% or 100%)	Recycled aluminium	Aluminium production, secondary, from new scrap, at plant	Result	RER	Not existing in 3.7.1 so 3.2.2 used, and with CA or CN electricity	
				Aluminium production, secondary, from old scrap, at plant	Result	RER		
		18035 cm ³ (19.86 kg)	Wood	Lath, softwood, raw, air drying to $u = 20\%$	Result	Europe without Switzerland	u : moisture content	
	Naval transport from China	210924 kgkm	Structure					
		51772 kgkm	Reflector (1 set)	Transport, freight, sea, container ship	Result	GLO	Shanghai to Rotterdam	
52731 kgkm		Pot holder						
Naval transport from Canada	182123 kgkm	Structure						
	44704 kgkm	Reflector (1 set)	Transport, freight, sea, container ship	Result	GLO	Vancouver to Rotterdam		
	45532 kgkm	Pot holder						

	kgkm						
Road transport	10955 kgkm	Structure					
	2705 kgkm	Reflector (1 set)	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER		Rotterdam to Altötting
	2739 kgkm	Pot holder					
	30321 kgkm	Complete parabola (with 4 set of reflectors)	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER		Altötting to Toulouse
	18591 kgkm	Pot holder and 4 sets of reflectors	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER		Altötting to Toulouse
End of life considering the replacement	5.41 kg or 3.36 kg for wooden structure	Aluminium	Treatment of waste aluminium, sanitary landfill	Unit	RoW		With French electricity
	16.39 kg or 10.19 kg for wooden structure	Recycled aluminium	Treatment of aluminium post-consumer, by collecting, sorting, cleaning, pressing	Unit	RER		With French electricity
	0.05 kg or 0.07 kg for wooden structure	Steel	Treatment of scrap steel, inert material landfill	Result	Europe without Switzerland		
	0.25 kg or 0.34 kg for wooden structure	Recycled steel	Sorting and pressing of iron scrap	Unit	RER		With French electricity
	76.44	Wood	Treatment of waste wood, post-consumer, sorting and shredding	Result	RoW		For one wooden structure

Table 2: Complete life cycle inventory of the induction hob studied, and ecoinvent database equivalence

Device	Component	Quantity	Process	Ecoinvent activity ¹	Type	Area ²	Comment ²
Induction hob	Housing	237.85 g	Lower housing	Polypropylene (PP) production, granulate	Unit	RoW	With CN electricity
				Injection moulding	Unit	RoW	With CN electricity
	73.24 g	Glass housing	Acrylonitrile-butadiene-styrene (ABS) copolymer	Result	RoW		

			production			
			Injection moulding	Unit	RoW	With CN electricity
	971.34 g	Ceramic glass	Flat glass production, uncoated	Unit	RoW	With CN electricity
			Tempering, flat glass	Result	RoW	
Coil assembly	112.02 g	Coil	Copper production, cathode, solvent extraction and electrowinning process	Unit	GLO	With CN electricity and ammonia
			wire drawing, copper	Unit	RoW	With CN electricity
	62.04 g	Coil support	PP production, granulate	Unit	RoW	With CN electricity
			Injection moulding	Unit	RoW	With CN electricity
	128.39 g	Magnetic field control bars	Ferrite production	Unit	GLO	With CN electricity
	23.69 g	Magnetic insulator	Aluminium production, primary, ingot	Unit	RoW	With CN electricity
			Sheet rolling, aluminium	Unit	RoW	With CN electricity
	3 sec	Magnetic insulator cutting	Laser machining, metal, with YAG-laser, 200W power	Result	RoW	[32]
	4.1 g	Fuse and resistor maintainer	Synthetic rubber production	Unit	RoW	With CN electricity and nitrogen
			Injection moulding	Unit	RoW	With CN electricity
	0.08 g	Resistor	Resistor production, metal film type, through-hole mounting	Result	GLO	
Electronic card	5.05 g	Electrolytic capacitor	Capacitor, electrolytic type, < 2 cm height	Result	GLO	
	52.05 g	Film type capacitor	Capacitor production, film type, for through-hole mounting	Result	GLO	
	0.12 g	Capacitor	Capacitor production, surface-mounted	Result	GLO	
	209.46 g	Printed circuit	Printed wiring board production, for through-hole mounting, Pb containing surface	Unit	GLO	With CN electricity
	0.29 g	Printed circuit	Printed wiring board	Unit	GLO	With CN

		production, for surface mounting, Pb containing surface			electricity
3.90 g	Display	Liquid crystal display production, minor components, auxiliaries and assembly effort	Unit	GLO	With CN electricity and ammonia
0.94 g	LED	light emitting diode production [GLO]	Result	GLO	
0.03	Diode	diode production, glass-, for surface-mounting [GLO]	Result	GLO	
1.71 g	Resistor	Resistor production, metal film type, through-hole mounting	Result	GLO	
0.16 g	Resistor	Resistor production, surface-mounted	Result	GLO	
0.32 g	Variable resistor	Potentiometer production, unspecified	Result	GLO	
2.89 g	IC memories	Integrated circuit production, memory type	Unit	GLO	With CN electricity
2.80 g	Transformer	Transformer production, low voltage use	Result	GLO	
49.36 g	Inductor	Inductor production, ring core choke type	Result	GLO	
0.32 g	Transistor	Transistor production, wired, small size, through-hole mounting	Result	GLO	
6.12 g	Transistor	Transistor production, wired, big size, through-hole mounting	Result	GLO	
0.03 g	Transistor	Transistor production, surface-mounted	Result	GLO	
7.02 g	Rectifier diode	Diode production, glass-, for through-hole mounting	Result	GLO	
		Diode production, surface-mounted	Result	GLO	
58.27 g	Heat sink	Aluminium production, primary, ingot	Result	CN	
		Impact extrusion of aluminium, 3 strokes	Result	RoW	

	5.52 g	Springs	Steel production, chromium steel 18/8, hot rolled	Result	RoW	
			Metal working, average, for chromium steel product manufacturing	Result	RoW	
Wiring	115 cm	Power supply	Cable production, connector for computer, without plugs	Result	GLO	
	1 unit	Plug	Plug production, inlet and outlet, for computer cable	Result	GLO	
	1 unit	Fan	Fan production, for power supply unit, desktop computer	Result	GLO	
	28.40 g	Filter	Ferrite production	Unit	GLO	With CN electricity
	1.62 g	Wire insulation	Polyvinylchloride production, bulk polymerisation	Result	RoW	
			Injection moulding	Unit	RoW	With CN electricity
	1.41 g	Wire	Copper production, cathode, solvent extraction and electrowinning process	Unit	RoW	With CN electricity and ammonia
			Wire drawing	Unit	RoW	With CN electricity
Screws and bolts	13.10 g	Steel production	Steel production, chromium steel 18/8, hot rolled	Result	RER or RoW	With DE or CN electricity
		Screw head formation, bolt shaping	Impact extrusion of steel, cold deformation stroke	Unit	RER or RoW	With DE or CN electricity
		Threading	Hot rolling, steel	Unit	Europe without Austria or RoW	With DE or CN electricity
Primary Energy	83935.15 kWh	Electricity	Market group for electricity, medium voltage	Result	FR	Use phase
Transport	39668 kgkm	Naval transport (for 1 hob)	Transport, freight, sea, container ship	Result	GLO	Shanghai to Rotterdam
	2363 kgkm	Road transport (for 1 hob)	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER	Rotterdam to Toulouse

End of life considering the replacement	68.85 g	Aluminium	Treatment of waste aluminium, sanitary landfill	Unit	RoW	With French electricity
	258.99 g	Recycled aluminium	Treatment of aluminium post-consumer, by collecting, sorting, cleaning, pressing	Unit	RER	With French electricity
	12.65 g	Steel	Treatment of scrap steel, inert material landfill	Result	Europe without Switzerland	
	61.8 g	Recycled steel	Sorting and pressing of iron scrap	Unit	RER	With French electricity
	700.38 g	Electronics components	Treatment of waste electric and electronic equipment, shredding	Unit	GLO	With French electricity
	210.76 g	Printed board	Treatment of scrap printed boards, shredding and separation	Result	RoW	
	358.21 g	Polymers and plastics landfilling	Treatment of waste plastic, mixture, sanitary landfill	Unit	RoW	With French electricity
	761.18 g	Polymers and plastics incineration	Treatment of waste plastic, mixture, municipal incineration	Result	RoW	
	373.13 g	Recycling polymers and plastics	Plastic flake production, consumer electronics, for recycling, by grinding/shredding, formal sector	Unit	IN	
	16.4 g	Rubber	Treatment of waste rubber, unspecified, municipal incineration	Unit	Europe without Switzerland	With French decarbonised water
	499.76 g	Wire and cable	Treatment of waste, electrical and electronic cables, open burning	Result	RoW	
	2642 g	Glass incineration	Treatment of waste glass, municipal incineration	Result	RoW	
	1243 g	Glass landfilling	Treatment of waste glass, sanitary landfill	Unit	GLO	With French electricity
448.08 g	Copper	Treatment of scrap copper, municipal incineration	Result	Europe without Switzerland		

Table 3: Complete life cycle inventory of the gas hob studied, and ecoinvent database equivalence

Device	Component	Quantity	Process	Ecoinvent activity ¹	Type	Area ²	Comment ²
Gas hob	Housing	486.69 g	Sides and top	steel production, chromium steel 18/8, hot rolled	Result	RoW	
				Sheet rolling, steel	Unit	RoW	With CN electricity
				Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
		3843.27 cm ²	Sides and top coating	Hard chromium coating, electroplating, steel substrate, 0.14mm thickness	Unit	RoW	With CN electricity
		80.37 g	Sides reinforcer and burner support	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
				Sheet rolling, steel	Unit	RoW	With CN electricity
				Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
		516.64 cm ²	Sides reinforcer and burner support coating	Zinc coating, pieces	Unit	RoW	With CN ammonia and electricity
		23.6 g	Support and gas opening potentiometer	Acrylonitrile-butadiene-styrene (ABS) copolymer production	Result	RoW	
				Injection moulding	Unit	RoW	With CN electricity
		193.4 g	Pot holder	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
				Sheet rolling, steel	Unit	RoW	With CN electricity
				Impact extrusion of steel, cold, deformation stroke	Unit	RoW	With CN electricity
		3 sec	Pot holder cutting	Laser machining, metal, with CO ₂ -laser, 2000 W power	Unit	RoW	With CN electricity, [33]
755.15 cm ²	Pot holder coating	Powder coating, steel	Unit	RoW	With CN electricity and decarbonised water		
Burner	Burner	443.10 g	Burner	cast iron production	Unit	Row	With CN

assembly			electricity and coal		
		casting, steel, lost-wax	Unit	RoW	With CN electricity
284.87 cm ²	Burner coating	powder coating, steel	Unit	RoW	With CN electricity and decarbonised water
22.23 g	Hose coupling	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Casting, steel, lost-wax	Unit	RoW	With CN electricity and aluminium oxide
19.41 cm ²	Hose coupling coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
60.91 g	Rigid hose	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Section bar rolling, steel	Result	RoW	
159.04 cm ²	Rigid hose coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
12.12 g	Gas setter potentiometer	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Steel turning, average, computer numerical controlled	Unit	RoW	With CN electricity
4.96 cm ²	Gas setter potentiometer coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
1.94 g	Drilled washer	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
5.12 cm ²	Drilled washer coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
12.55 g	Air opening setter washer	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
40.66 cm ²	Air opening setter washer	Zinc coating	Unit	RoW	With CN electricity and

	coating				ammonia
5.43 g	Spark plug protection	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
20 cm ²	Spark plug protection coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
7.09 g	Spark plug holder	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
		Deep drawing, steel, 650 kN press, automode	Unit	RoW	With CN electricity
29.89 cm ²	Spark plug holder coating	Zinc coating	Unit	RoW	With CN electricity and ammonia
1.93 g	Spring	steel production, chromium steel 18/8, hot rolled	Result	RoW	
		metal working, average for chromium steel product manufacturing	Result	RoW	
0.32 g	Seal	synthetic rubber production	Unit	RoW	With CN electricity and nitrogen
		injection moulding [RoW]	Unit	RoW	With CN electricity
31.13 g	Aluminium housing	aluminium production, primary, ingot	Result	CN	
		casting, aluminium, lost-wax	Unit	RoW	With CN electricity, aluminium, ammonia, and nitric acid
11.69 g	Gas line pieces	Brass production	Unit	RoW	with CN electricity
		casting, brass	Unit	RoW	With CN electricity
		brass turning, average, computer numerical controlled	Unit	RoW	With CN electricity
960 g	Hose	Synthetic rubber production	Unit	RoW	With CN electricity and nitrogen
		Extrusion, plastic pipes	Unit	RER	With CN electricity

	0.72 g	Pin	steel production, chromium steel 18/8, hot rolled	Result	RoW	
			chromium steel turning, average, computer numerical controlled	Result	RoW	With CN electricity
Spark plug assembly	0.37 g	Plug tip	steel production, converter, low-alloyed	Unit	RoW	With CN electricity
			Wire drawing, steel	Unit	RoW	With CN electricity
	3.11 g	Tip holder	Sanitary ceramics production	Unit	RoW	With CN electricity
	2.21 g	Cable	cable production, unspecified	Result	RoW	
	0.99 g	Housing	PP production, granulate	Result	RoW	With CN electricity
			Injection moulding	Unit	RoW	With CN electricity
	1.92 g	Piezoelectric ceramics	Sanitary ceramics production	Unit	RoW	With CN electricity [32]
	5.54 g	Piezoelectric hammer	steel production, converter, low-alloyed	Unit	RoW	With CN electricity
			Casting, steel, lost-wax	Unit	RoW	With CN electricity
	1.15 g	Housing tips	steel production, converter, low-alloyed	Unit	RoW	With CN electricity
			steel turning, average, computer numerical controlled	Unit	RoW	With CN electricity
	0.23 g	Piezoelectric maintainer	steel production, converter, low-alloyed	Unit	RoW	With CN electricity
			Wire drawing, steel	Unit	RoW	With CN electricity
Screws and bolts	34.34 g	Steel production	Steel production, chromium steel 18/8, hot rolled	Result	RER or RoW	With DE or CN electricity
		Screw head formation, bolt shaping	Impact extrusion of steel, cold deformation stroke	Unit	RER or RoW	With DE or CN electricity
		Threading	Hot rolling, steel	Unit	Europe without Austria or RoW	With DE or CN electricity
Primary	1131.60	Natural gas	Market for natural	Result	FR	Use phase

Energy	m ³		gas, high pressure			
Transport	46117 kgkm	Naval transport (for 1 gas hob)	Transport, freight, sea, container ship	Result	GLO	Shanghai to Rotterdam
	2747 kgkm	Road transport (for 1 gas hob)	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER	Rotterdam to Toulouse
End of life considering the replacement	13.07 g	Aluminium	Treatment of waste aluminium, sanitary landfill	Unit	RoW	With French electricity
	49.19 g	Recycled aluminium	Treatment of aluminium post-consumer, by collecting, sorting, cleaning, pressing	Unit	RER	With French electricity
	477.52 g	Steel	Treatment of scrap steel, inert material landfill	Result	Europe without Switzerland	
	2247.37 g	Recycled steel	Sorting and pressing of iron scrap	Unit	RER	With French electricity
	33.44 g	Inert waste	Treatment of inert waste, sanitary landfill	Unit	Europe without Switzerland	With French electricity
	461.43 g	Polymers and plastics landfilling	Treatment of waste plastic, mixture, sanitary landfill	Unit	RoW	With French electricity
	980.54 g	Polymers and plastics incineration	Treatment of waste plastic, mixture, municipal incineration	Result	RoW	
	480.66 g	Recycling polymers and plastics	Plastic flake production, consumer electronics, for recycling, by grinding/shredding, formal sector	Unit	IN	
4.42 g	Wire and cable	Treatment of waste, electrical and electronic cables, open burning	Result	RoW		

Table 4: Complete life cycle inventory of the electric plate studied, and ecoinvent database equivalence

Device	Component	Quantity	Process	Ecoinvent activity ¹	Type	Area ²	Comment ²
Electric plate	Housing	419.59 g	Housing	Steel production, converter, low-alloyed	Unit	RoW	With CN electricity
				Sheet rolling, steel	Unit	RoW	With CN electricity
				Deep drawing, steel,	Unit	RoW	With CN

			3500 kN press, automode			electricity
	3605.6 cm ²	Housing coating	Powder coating, steel	Unit	RoW	With CN electricity and decarbonised water
	9.4 g	Thermostat	Nylon 6 production	Result	RoW	
			Injection moulding	Unit	RoW	With CN electricity
	220.22 g	Relays	Switch, toggle type	Result	RoW	
	20.16 g	Wire junction casing	PP production, granulate	Result	RoW	
			Injection moulding	Unit	RoW	With CN electricity
	10.8 g	Support	Synthetic rubber production	Result	RoW	With CN nitrogen and electricity
			Injection moulding	Result	RoW	With CN electricity
Hot plate assembly	861.21 g	Hot plate	Cast iron production	Unit	RoW	With CN electricity and hard coal
			Casting, steel, lost- wax	Unit	RoW	With CN electricity
	90.34 g	Heating resistor exterior	Steel production, converter, low- alloyed	Result	RoW	Outer part of the resistance
			Section bar extrusion	Result	RoW	
	52.84 g	Heating resistor filling	Refractory production, basic, packed	Unit	RoW	With CN electricity
	27.27 g	Heating resistor interior	Iron-Nickel- Chromium alloy production	Unit	RoW	With CN electricity
			Metal working, average for steel product manufacturing	Result	RoW	
	253.99 g	Refractory cement	Refractory production, basic, packed	Unit	RoW	With CN electricity
	40.72 g	Insulator	Glass wool mat production	Unit	RoW	With CN ammonia, urea, and electricity
	62.13 g	Insulator housing	Steel production, converter, low alloyed	Unit	RoW	With CN electricity
		Sheet rolling, steel	Unit	RoW	With CN electricity	
		Deep drawing, steel, 3500 kN press,	Unit	RoW	With CN electricity	

			automode			
	478.2 cm ²	Insulator housing coating	Zinc coating, pieces	Unit	RoW	With CN ammonia and electricity
	100.75 g	Lower housing	Steel production, converter, low alloyed	Unit	RoW	With CN electricity
			Sheet rolling, steel	Unit	RoW	With CN electricity
			Deep drawing, steel, 3500 kN press, automode	Unit	RoW	With CN electricity
	753.2 cm ²	Lower housing coating	Powder coating, steel	Unit	RoW	With CN electricity and decarbonised water
Wiring	255 cm	Power supply	cable production, connector for computer, without plugs	Unit	GLO	With CN electricity
	1 unit	Plug	plug production, inlet and outlet, for computer cable	Unit	GLO	With CN electricity
	0.29 g	LED	Light emitting diode production	Result	GLO	
	0.08 g	Resistor	Resistor production, metal film type, through-hole mounting	Result	GLO	
	5.65 g	Electric wire insulator	Silicone product production	Unit	RoW	With CN electricity
			Injection moulding	Unit	RoW	With CN electricity
	6.92 g	Electric wire	Copper production, cathode, solvent extraction and electrowinning process	Unit	GLO	With CN ammonia and electricity
			Wire drawing, copper	Unit	RoW	With CN electricity
	3.46 g	Electric wire protection	Glass fibre production	Unit	RoW	With CN electricity
			Weaving of synthetic fibre, for industrial use	Unit	GLO	With CN electricity
Screws and bolts	28.37 g	Steel production	Steel production, chromium steel 18/8, hot rolled	Result	RER or RoW	With DE or CN electricity
		Screw head formation, bolt shaping	Impact extrusion of steel, cold deformation stroke	Unit	RER or RoW	With DE or CN electricity
		Threading	Hot rolling, steel	Unit	Europe	With DE or CN

					without Austria or RoW	electricity
Primary Energy	10468.19 kWh	Electricity	Market group for electricity, medium voltage	Result	FR	Use phase
Transport	47894 kgkm	Naval	Transport, freight, sea, container ship	Result	GLO	Shanghai to Rotterdam
	2852 kgkm	Road	Transport, freight, lorry 16-32 metric ton, EURO5	Result	RER	Rotterdam to Toulouse
End of life considering the replacement	1080.97 g	Steel	Treatment of scrap steel, inert material landfill	Result	Europe without Switzerland	
	5277.68 g	Recycled steel	Sorting and pressing of iron scrap	Unit	RER	With French electricity
	38.75 g	Polymers and plastics landfilling	Treatment of waste plastic, mixture, sanitary landfill	Unit	RoW	With French electricity
	82.33 g	Polymers and plastics incineration	Treatment of waste plastic, mixture, municipal incineration	Result	RoW	
	40.36 g	Polymers and plastics recycling	Plastic flake production, consumer electronics, for recycling, by grinding/shredding, formal sector	Unit	IN	
	881.49 g	Electronics components	Treatment of waste electric and electronic equipment, shredding	Unit	GLO	With French electricity
	162.88 g	Glass wool	Treatment of waste mineral wool, collection for final disposal	Result	Europe without Switzerland	
	502.37 g	Wire and cable	Treatment of waste, electrical and electronic cables, open burning	Result	RoW	
	1227.35 g	Inert waste	Treatment of inert waste, sanitary landfill	Unit	Europe without Switzerland	With French electricity

The production supply chain of the solar cooker is inspired by the one of the EG-Solar SK14 cooker, for which the raw materials are produced overseas (China or Canada here) but the manufacturing and the packing are made in Germany. Moreover, as mentioned in 3.1.1, each assessed solar cooker was considered with the same reflector and the same pot holder regardless of the structure material. Concerning aluminium, the following sources were considered: Chinese aluminium from bauxite, Canadian aluminium from bauxite, Chinese aluminium with 35% recycled, Canadian aluminium with 35% recycled and 100% recycled aluminium. The recycled aluminium is only available from Europe in ecoinvent database. For the screws and bolts of the solar cooker, European chromium steel was considered. The same production methods and materials were considered for the screws of all the devices regardless of the screwed materials: only quantity and shape varied.

The production supply chains of the induction hob, the electric plate and the gas hob correspond to those of the Severin plate KP1071, the Proline HPO15W and the Ribimex PRF315, respectively. Production and assembly of these devices take place in China. Components with different sizes and structures but with the same function and classification were grouped under the same ecoinvent database classification (e.g. screws). When processes, materials or products were not present in the database, the closest proxy was used; in specific cases minor components were not considered (e.g. fuses) because of the lack of information.

For the aluminium solar cooker, it was assumed that the screws, bolts, and structure do not need to be replaced along the 40 years of utilization. Nonetheless, for the reflectors, according to the questioned users, a lifetime of 10 years was assumed, thus four sets are needed during the life span of the cooker. A lifetime of 10 years was considered for the wood structure. In the case of the induction hob and the electric plate, a lifetime of 10 years was considered because of the presence of electronic components: it was assumed that such products are not repairable part by part, so they have to be replaced completely. The gas hose needs to be replaced every 10 years for safety purpose, and the gas hob every 20 years since it does not contain any electronic parts.

Transportation of materials between the different manufacturing sites was included in the LCA model. The routes were identified by questioning the manufacturers and, if no information was obtained, the largest production site and the most used transportation path were chosen. For the products manufactured in China, the road transport with the European EURO5 standard and sea freight transport between harbours was considered. The assembly of the solar cooker is performed in Germany, so that the road transportation was calculated for each of its components. For all devices, the travel between the assembly site (in Germany for the solar cooker and in China for the induction hob, electric plate and gas hob) and the using site was considered. In the case of the wood solar device, since the wood is considered recovered from pallet, no transportation was considered because of its local availability.

The inventory was completed with data from ecoinvent database for the background processes (energy and raw materials production, transportation means, etc.). The energy consumption (electricity or natural gas) during the use phase of the three conventional cooking devices was evaluated from the experimental data described in section 3.2 and further detailed in section 4.1. With respect to the end of life, each device was treated in France. The materials were grouped by type as much as possible and the processes of treatment and disposal were either identified from the literature or by questioning the professionals in the sector. Moreover, when the treatment or disposal of the materials or products was not clearly defined, we used the market type of activity corresponding to a mix of several balanced processes (landfill, incineration, recycling).

3.3.3. Life cycle impact assessment

To evaluate the environmental impacts, the ReCiPe method with hierarchist cultural perspective was used, at mid-point and end-point. ReCiPe midpoint evaluates 18 impact categories, expressed in specific units by category (e.g. climate change is expressed in kg of CO_{2e}). ReCiPe endpoint calculates 18 damage categories expressed in “points”, which can be grouped in 3 areas of protection (human health, ecosystem quality and resource depletion). Impact scores can further be aggregated into one unique score.

4. Results and discussion

4.1. LCI analysis

The induction hob was decomposed in five parts: the electronic card, the coil assembly, the housing, the wiring and the screws. The components or materials with no equivalent in the ecoinvent database represent 0.3% of the total weight only (small polymers and metal parts); they were therefore neglected. The electric plate was decomposed in four parts: the housing, the hot plate, the wires and the screws; here the neglected part represents 0.21% of the total mass. The gas hob was decomposed in three parts: the housing, the burner assembly and the screws; the neglected part represented 0.32% mass. The components, their number and masses are listed in SI Table C2, C3 and C4. The complete inventory and was obtained following the method of Elduque *et al.*, which consists in weighting all the components and grouping them by type [34]. All collected and calculated data are available at <https://doi.org/10.48531/JBRU.CALMIP/GJHIIIH> .

Figure 5 shows the evolution of efficiency (see Equation 1) as a function of the thermostat value for each device. For the induction hob, Figure 5-a, efficiency increases markedly from *ca.* 60% to 70% between thermostats 2 to 4, and then plateaus or rise smoothly. The highest efficiency (74.02%) was reached for the 10th level, details in SI Table B1. For the gas hob, Figure 5-b, the burner sizes and knob positions are ordered according to the gas flow, which increases monotonically from S1 to L4, details in see SI Table B2. The efficiency is not monotonic and displays a maximum for the small burner in position 4. This tendency is probably due to the fact that, the larger the burner, the higher the energy lost on the sides of the pot. The maximum efficiency reached is 51.5%. For the electric plate, Figure 5-c shows that efficiency increases with the thermostat level, details in SI Table B3. With the thermostat 1, it was not possible to reach 90°C, therefore the calculation was performed with 86°C at maximum and not 90°C. The maximum efficiency reaches 63.2% for thermostat 6.

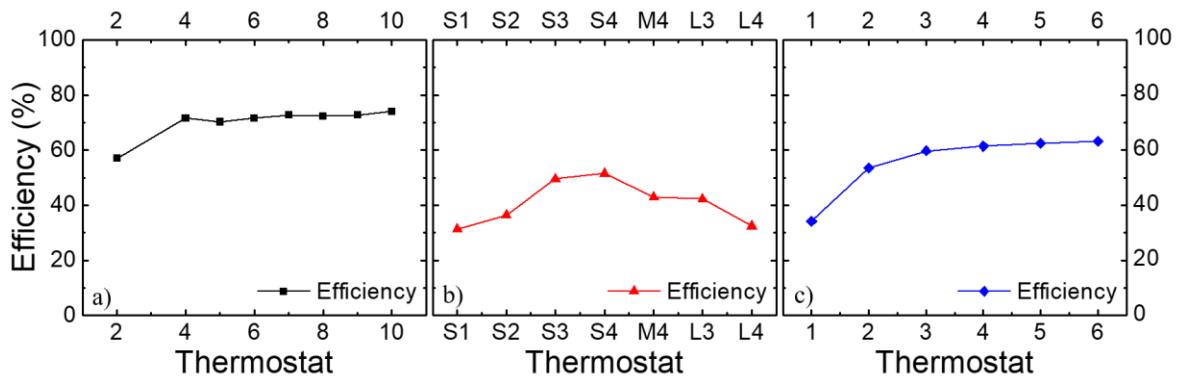


Figure 5: Efficiency at different thermostats for the a) induction hob, b) gas hob and c) electric plate. For the gas hob, the S, M and L letters correspond to the burner size.

Table 5 summarizes experimental results including the best efficiency value, which have thus been used in the LCIA to calculate the amount of electricity or gas consumed by each device. The most efficient and fastest device is the induction hob.

Table 5: Main results related to the experiments consisting in heating 2L of water from 25°C to 90°C with the three conventional cooking appliances. Indicated values correspond to the highest efficiency for each device.

Cooking appliance	Consumption (kWh)	Rising time (25°C to 90°C) (min)	Efficiency (%)
Induction hob	0.20	6.5	74.02
Electric plate	0.24	14.0	65.3
Gas hob	0.29	18.5	53.2
Solar cooker		31.8	

4.2. Environmental impact results

4.2.1. Solar cooker

4.2.1.1. Effect on impacts of different materials and different origins and contribution analysis

The sensitivity of LCA results to the type of material and its origin is investigated hereafter. Figure 6 plots all mid-point impacts for the ten variants of solar cooker normalised, for each impact category, by the maximum impact value. Because the main aluminium producer is China, the solar device made out of Chinese aluminium will be considered as the reference one in the following. As expected, the solar cooker made of wood and 100% recycled aluminium has globally the lowest impacts and the reference parabola dominates most of the indicator, the reference device performs better on agricultural land occupation only. For the cooker made of wood and 100% recycled aluminium, wood production (156 m²) is the largest share for the agricultural land occupation value (159 m²). The natural land transformation and ionising radiation is also higher for all the Canadian aluminium containing cookers, probably due to more use of nuclear power in the electricity production technique and a larger use of oil to heat the aluminium production in Canada. This analysis clearly demonstrates that the use of

recycled metals and wood gives a large ecological advantage to the product. The detailed mid-point results are provided in SI Table D1 and D3.

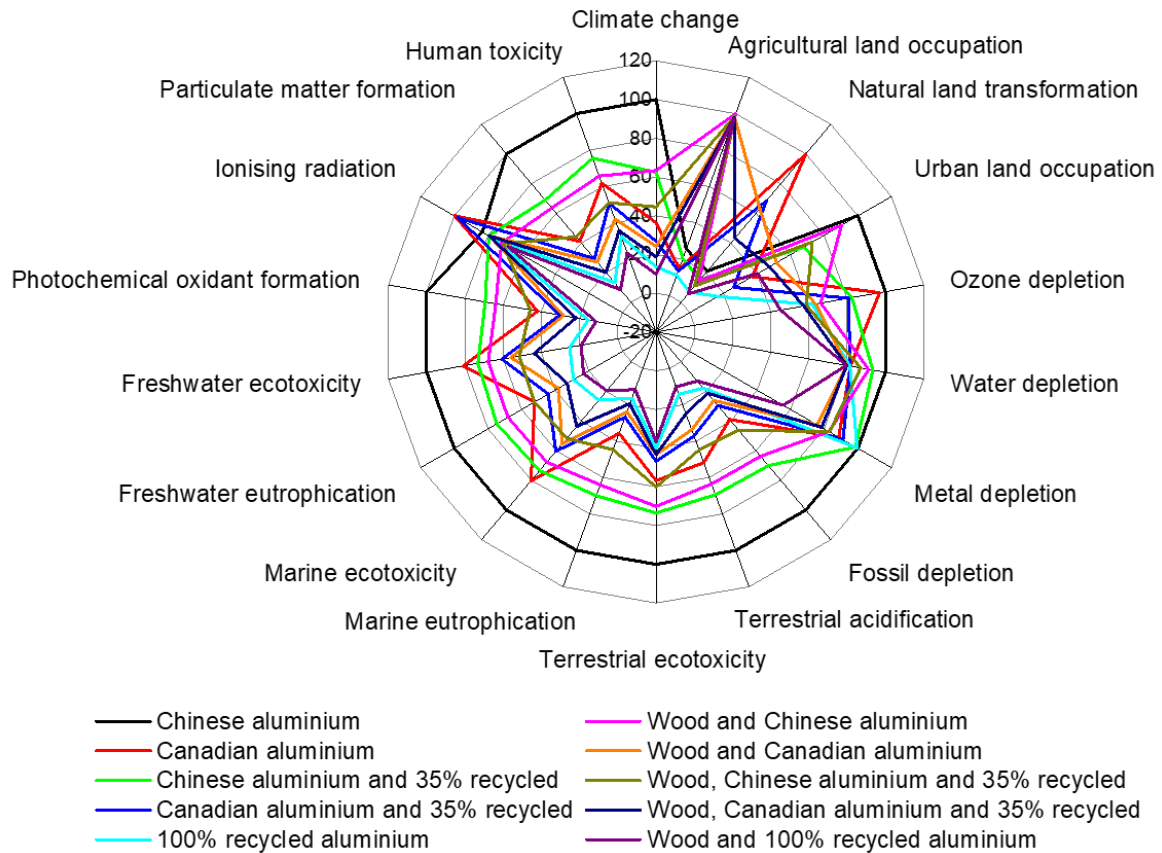


Figure 6: Comparison between the mid-point values of all the variants of solar cookers. The impact results were normalized by the maximum value in each impact category. Cradle-to-user boundaries.

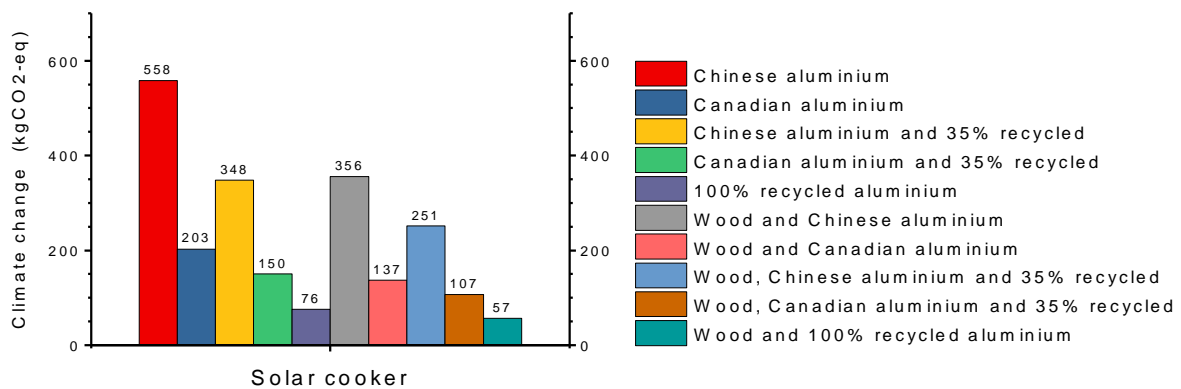


Figure 7: Climate change mid-point impact (kgCO₂-eq) for all the variants of solar cooker (cradle-to-user).

Because climate change is usually identified as the main impact related to the ecological issues, Figure 7 shows the mid-point climate change indicator values for all variants of

material combinations. The use of Canadian aluminium decreases significantly the climate change impact of the solar cookers from 558 kgCO_{2eq} (in the case of Chinese aluminium) to 203 kgCO_{2eq}. The difference comes from the difference in electricity mix and used technologies, implying large differences in carbon dioxide and methane emissions (766 gCO_{2eq}/kWh and 166 gCO_{2eq}/kWh for Chinese and Canadian electricity production, respectively). The best device lowers the climate change impact 10 times with respect to the reference device.

The details of the mid-points result of the reference parabola are provided in SI Figure D1. Figure 8 shows the contribution of the different processes (including transportation to the use site in France) on mid-point climate change and fossil depletion impacts, which represent 558 kgCO_{2eq} and 128 kgOil_{eq}, respectively. For clarity, only processes with significant impact were plotted in the caption. Aluminium production is responsible of 86% and 89% of fossil depletion and climate change impacts, respectively, followed by the anodising of the

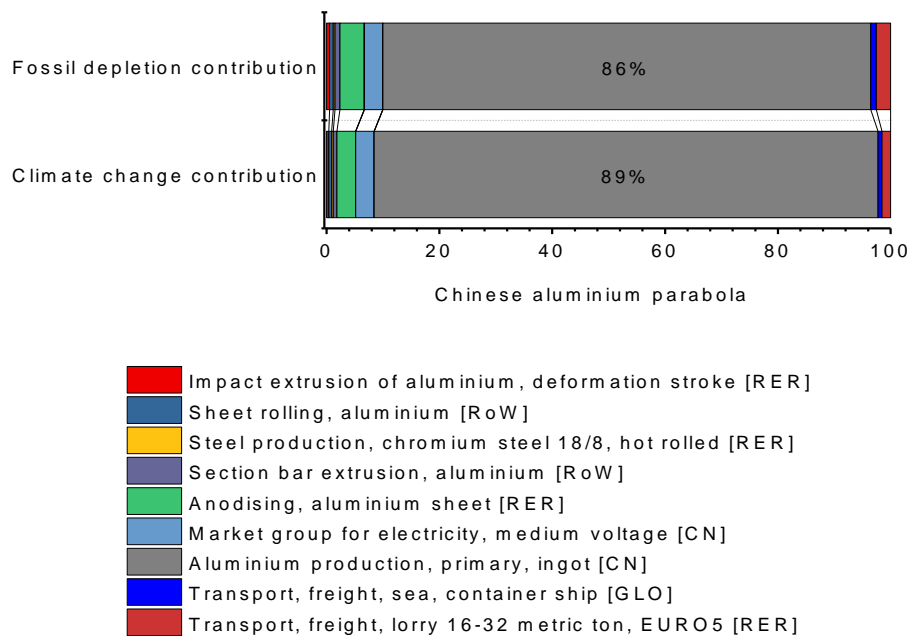


Figure 8: Relative contribution of the main fabrication processes to the mid-point impacts on climate change and fossil depletion for the reference solar cooker. Market group for electricity is related to the mean electricity mix in China.

aluminium sheets and the Chinese electricity production.

4.2.1.2. Cradle-to-grave impact results: influence of the end-of-life stage

The complete life cycle of the solar cookers includes the end-of life processes. Different end-of-life options exist, as presented in section 3 (landfill, incineration, recycling). Among the various options, recycling permits to improve the environmental performance of most cookers.

Figure 9 shows the life cycle impact results of the reference solar cooker, negative values representing the avoided material impacts due to recycling (data available in SI table D2). For the reference solar cooker, recycling decreases the net impact values by 14% to 56% except

for the marine and freshwater ecotoxicity. Indeed, the treatment of scrap aluminium rises these impacts by a factor 30 (from 7 to 206 kg1.4-DCB_{eq}) and 34 (from 7 to 239 kg1.4-DCB_{eq}), respectively due to the aluminium scrap and to the copper scrap used during the process.

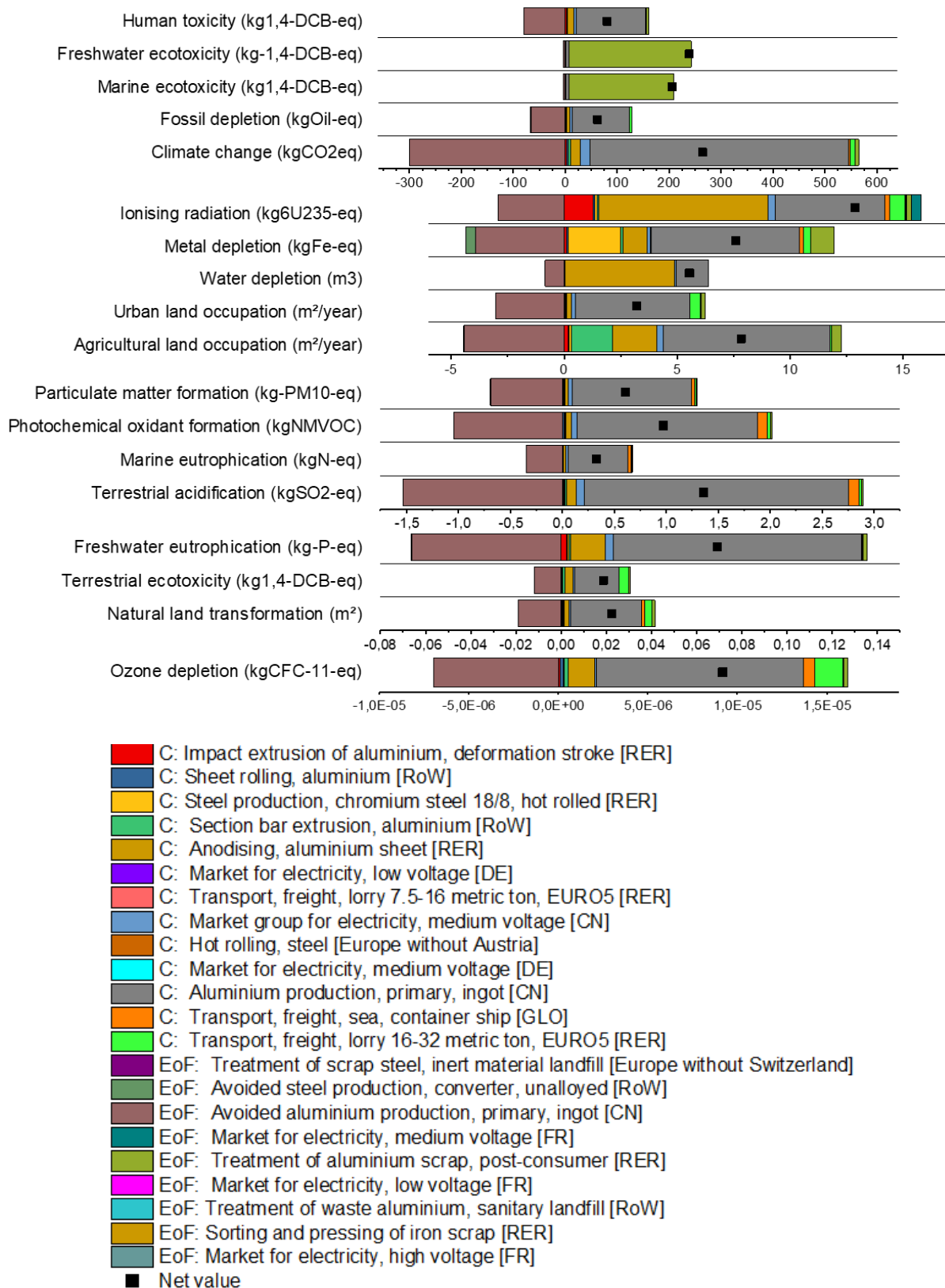


Figure 9: Detailed contribution analysis of the reference parabola with contribution of the end of life treatment (C: Construction processes, EoL: End of life processes)

In the case of the solar cooker made of wood and 100% recycled aluminium some impact indicators decrease while other drastically rise (data available in SI Table D4). Metal depletion and human toxicity decrease by 35% and 18% respectively, with respect to the cradle-to-use boundaries, due to the avoided primary aluminium and steel production. In contrast, marine and freshwater ecotoxicity impacts rise severely (from 1.4 to 127 kg1.4-DCB_{eq} and 1.4 to 147 kg1.4-DCB_{eq} respectively) because of the treatment of aluminium wastes. They however stay below the one of the reference solar cooker with its recycling. Concerning the climate change indicator, the impact decreases by 53% for the Chinese aluminium device whereas it increases by 2% for the cooker made of wood and 100% recycled aluminium. The results show that recycling markedly decreases the impact when primary resource is used in the product because it prevents the extraction and transformation of the mineral resources. Yet when recycled aluminium or wood are used in the manufacturing process, recycling induces a smaller decrease because the product dismantling and treatment generate additional impacts, which are non-negligible in the assessment of already optimized devices.

4.2.1.3. Damage approach

Table 6 displays the two higher ReCiPe end-point results for resource depletion (RD), human health (HH), and ecosystem quality (EQ) for the reference solar cooker; detailed results are available in SI Table D5. Noticeably, among the HH and EQ categories, climate change largely dominates: climate change indicator is approximately 2 and 22 times higher than the second type of damage in HH and EQ area respectively. In the RD category, fossil depletion dominates, being 11 times larger than the second criterion.

Table 6: The two highest ReCiPe end-point impacts of the Chinese aluminium parabola.

Device	Ecosystem quality (pt)		Human health (pt)		Resource depletion (pt)	
	Climate change	Agricultural land occupation	Climates changes	Particulate matter formation	Metal depletion	Fossil depletion
Reference device	9.77	0.44	15.5	6.77	15.3	1.42

Figure 10 unveils the RD, HH and EQ end-point scores for different solar cookers obtained by combining different materials from different origins, the end-point results are available in SI Table D5 and D7.

The device made out of Chinese aluminium largely dominates RD and HH categories. This is due to the coal consumption and the associated CO₂ emissions. These impacts are reduced when i) Canadian aluminium – produced with a less CO₂-intensive electricity – is used, ii) recycled aluminium is introduced, and iii) wood is used for the structure. In the end, solar cookers containing some Chinese aluminium have the largest impacts, even when wood or a moderate part of recycled aluminium replace a part of it. Figure 10 highlights that combining the three substitutions cited above dramatically reduces the impacts in RD and HH categories. For the EQ damage category, the wood and Chinese aluminium cooker has the largest impacts – in this case due to the use of wood –, followed by the 100% Chinese aluminium device. Whatever the aluminium origin, its partial substitution by wood always rises the EQ impact.

This is due to the agricultural land occupation indicator, which is high for wood. The EQ impact of Canadian and recycled aluminium are relatively low compared to the Chinese one. Thus, substituting them in the structure induces a larger increase of the EQ value compared to substituting the Chinese one. Finally, the solar cooker made with recycled aluminium has the lowest overall end-point impact (9.1 points), closely followed by the one made out of recycled aluminium and wood (12.1 points). However, when looking closely at the details of the impact indicators (see SI Table D5 and D7), one observes that the latter has lower end-points on 14 of the 17 criteria.

In term of end-point analysis, recycling decreases from 52.1 to 25.2 points the impacts of the Chinese aluminium device (data available in SI Table D6) and from 12.1 to 11.9 points the ones of the device made of wood and 100% recycled aluminium (data available in SI Table D8).

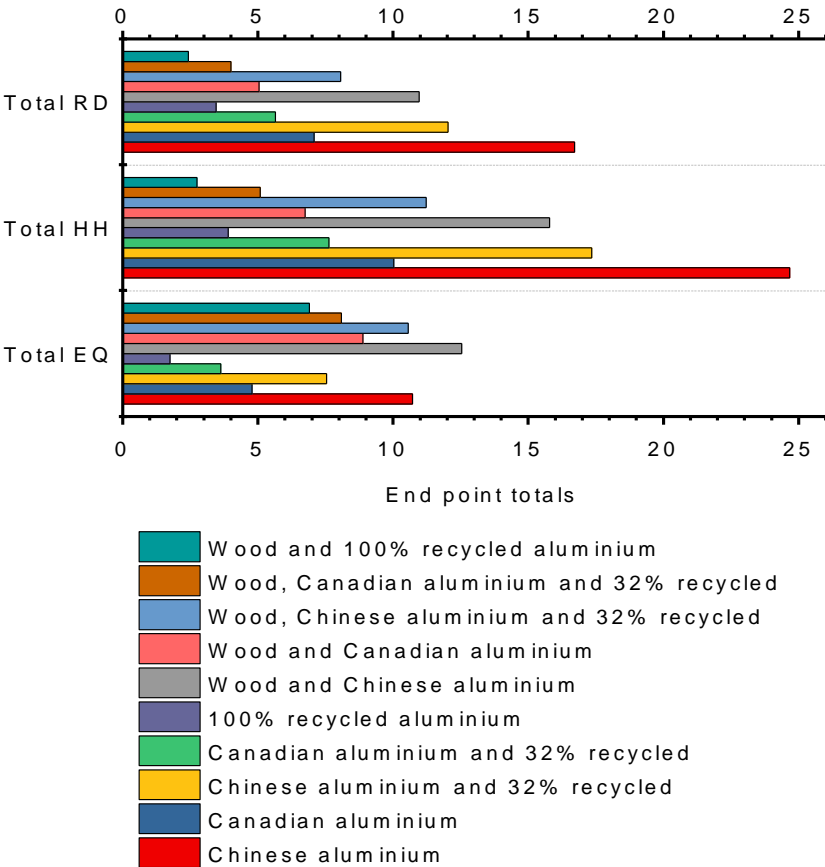


Figure 10: Total end-point results for resource depletion, human health and ecosystem quality for all the assessed solar cookers (cradle-to-user).

4.2.2. Conventional cookers

4.2.2.1. Cradle-to-user results of the conventional devices

To allow an easier comparison between the devices, all mid-point impacts for the three conventional appliances are reported normalised by the maximum impact value in Figure 11. This shows that the electric plate and the induction hob globally dominate the human health

(HH) and ecosystem quality (EQ) categories with a higher impact in each category for the former, largely due to its lower efficiency. Moreover, the gas hob has a very strong implication in the resource depletion (RD) category, except for water and metal depletion. The detailed results of the construction and use phases are provided in SI Table E1 and E2 for the mid-points. The climate change impacts of the construction phase (cradle-to-gate boundaries) represents 87.5 kgCO₂eq for the induction hob, 274.5 kgCO₂eq for the electric plate and 478 kgCO₂eq for the gas hob. They represent only 10%, 23% and 12% of the cradle-to-use climate change impact without considering end of life treatment, respectively.

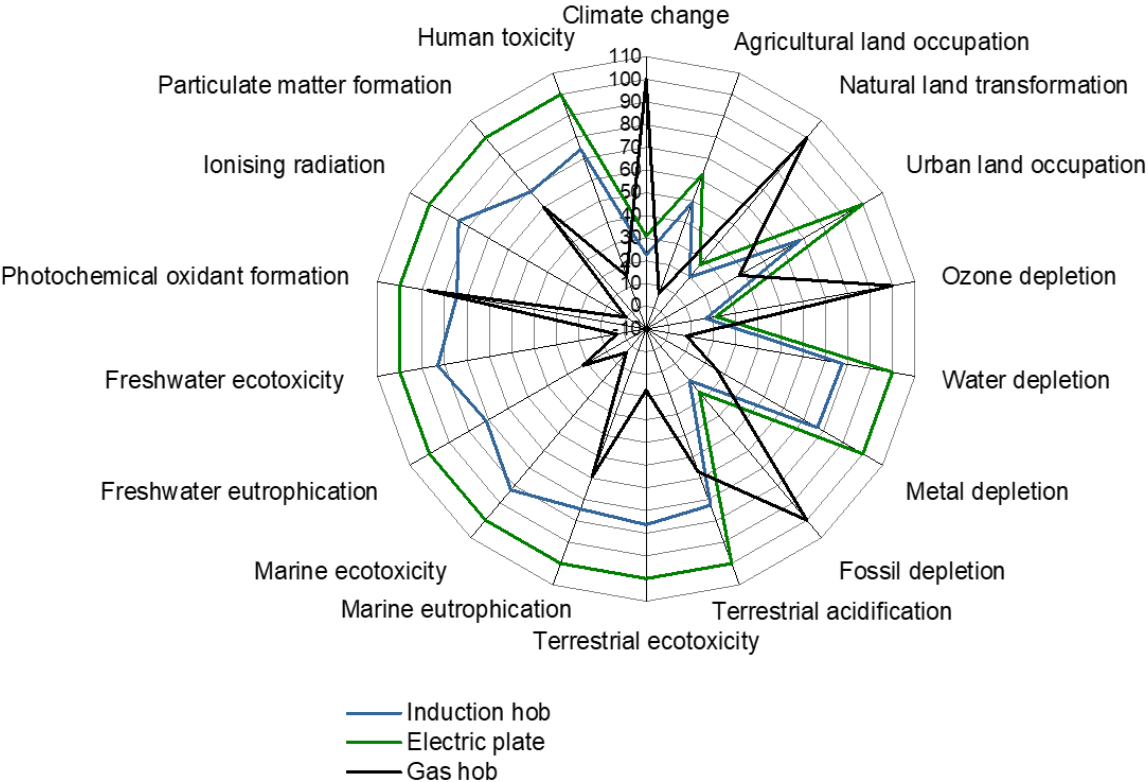


Figure 11: Comparison between the mid-point values of the 3 conventional appliances. The impact results were normalized by the maximum value in each impact category. Cradle-to-user boundaries.

4.2.2.2. Cradle-to-grave results of the conventional devices and contribution analysis

When the end of life treatment is considered and the mid-point results of the conventional cookers are broken down into the construction, use and end-of-life stages, the impact indicators are either dominated by the electric plate or the gas hob, except for marine and freshwater ecotoxicity due to the end-of-life stage of the induction hob. As shown in Table 7, for the induction hob and the electric plate, the use stage represents the major contributor for all impact categories, except metal depletion. At the opposite, for the gas hob device, 13 out of the 18 indicators are dominated by the construction phase, the 5 remaining impacts being climate change, natural land transformation, ozone depletion, fossil depletion and photochemical oxidant formation categories. They are all due to the use of natural gas.

For the induction hob, most mid-point indicators change by less than 2% when including the end-of-life treatment, except for the terrestrial ecotoxicity, which rises by 137% (as a result of waste cable treatment), and for the marine and freshwater ecotoxicity, which rises by 51% and 52% (both due to the treatment of scrap copper and scrap aluminium). Concerning the electric plate, similarly to the induction hob, most indicators do not vary by more than approximately 1% except for the terrestrial ecotoxicity, which rises by 108% because of the waste cable treatment. Finally, for the gas hob, the difference does not exceed 1% for 12 mid-point indicators but six indicators change slightly. The decreasing indicators are metal depletion, freshwater eutrophication and particulate matter formation with 4%, 2% and 1% of decrease, respectively, due to the avoided production of steel and aluminium. The increasing indicators are the terrestrial, the marine and the freshwater ecotoxicity with 5.5%, 6.1% and 7.6%, respectively, due to the treatment of electric and electronic cable for the first one and the treatment of aluminium for the two others.

The aggregated end-point impacts are of 358 points for the gas hob, 159 for the electric plate and 116 for the induction hob. The share between the construction phase and the use phase is of the same order of magnitude as the one provided above for the climate change impact *i.e.* 10%, 23% and 12% for the induction hob, the electric plate and the gas hob respectively. All end-point results are available in SI Table E3, E4 and SI Figure E1 for the end-points and the results cradle-to-grave are provided in SI Table E5.

4.2.3. Global comparison

In this section, the conventional cookers are compared with the overall most performant (wood and 100% recycled aluminium) and less performant solar cooker (Chinese aluminium). Figure 12 presents the mid-point impact results value of each impact category.

When only the construction phase is considered, the reference solar device dominates 8 impacts, the electric plate 9 impacts, while the device made of wood and 100% recycled aluminium overtakes the others only for agricultural land occupation (159 m² against 12 m² for the reference parabola). As previously demonstrated, this is due to the use of wood in the structure which accounts for 156 m².

There is no use stage impact in case of solar cookers while the use of the conventional devices requires electricity or gas. The energy used during this phase makes the conventional devices by far less performant than the solar cookers, as shown in Table 7. The solar cooker made of wood and 100% recycled aluminium has much lower impacts for most indicators compared to the conventional devices: the electric plate dominates 13 indicators, the gas hob 4 ones and the solar device made of wood and 100% recycled aluminium a single one. The climate change indicator of the reference solar cooker reaches 558 kg CO₂eq against 874 kgCO₂eq for the induction hob, 1196 kg CO₂eq for the electric plate and 3864 kg CO₂eq for the gas hob, which are mainly due to the electricity and natural gas consumption in the use stage. Electricity consumption also explains the dramatic increase of the ionising radiation impact from 5.8 to 5041 kg6U235eq for the induction hob, and from 18 to 5906 kg6U235eq for the electric plate, in reason of the large nuclear share in the French electricity mix.

End-of-life results show that only the reference solar cooker impacts are significantly lowered by the end-of-life treatment, and this for most indicators. The end-of-life treatment induces a large increase in the terrestrial ecotoxicity for the induction hob and the electric plate (as discussed in the previous section).

The net impacts are dominated by either the electric plate or the gas hob, except for the marine and freshwater ecotoxicity indicators, which are both dominated by the induction hob,

and for the agricultural land occupation, which is dominated by the solar cooker made of wood and Chinese aluminium. Noticeably, the solar cookers perform better for all indicators, which is mainly due to the fact that they do not consume energy during the use phase. Concerning the cradle-to-grave damage approach, the total ReCiPe end-point results show that the gas hob is the most damaging with 358 points followed by the electric plate, the induction hob, the Chinese aluminium parabola, the solar cooker made of wood and 100% recycled aluminium, the solar cooker made of 100% recycled aluminium, with 159, 116, 25, 12 and 8 points, respectively (see SI Table D6, D8 and E5).

Table 7: Cradle-to-grave mid-point-results for the conventional devices broken down by stage. C: construction, U: use, E: End-of-life, T: Total and red: highest value of the indicator

Device	Induction hob				Electric plate				Gas hob			
	C	U	E	T	C	U	E	T	C	U	E	T
Climate change (kgCO ₂ eq)	87.5	786.8	0.3	874.6	274.5	921.8	-8.21	1188	478	3386	-3.09	3861
Agricultural land occupation (m ² /year)	3.78	76.75	0.12	80.65	12.13	89.92	-0.08	102	9.7	1.06	-0.05	10.7
Natural land transformation (m ²)	0.014	0.15	1.92×10 ⁻⁴	0.17	0.043	0.18	-6.49E-04	0.22	0.0294	0.8	-3.33×10 ⁻⁴	0.83
Urban land occupation (m ² /year)	2.08	11.86	6.98×10 ⁻²	14.01	6.52	13.89	-0.08	20.34	5.66	1.94	-0.04	7.56
Ozone depletion (kgCFC-11-eq)	4.46×10 ⁻⁶	7.26×10 ⁻⁵	4.82×10 ⁻⁸	7.71×10⁻⁵	1.22×10 ⁻⁵	8.51×10 ⁻⁵	-3.81×10 ⁻⁷	9.69×10⁻⁵	6.04×10 ⁻⁶	4.55×10 ⁻⁴	-1.79×10 ⁻⁷	4.61E-04
Water depletion (m ³)	0.54	24	-3.10×10 ⁻³	25	3.14	28.5	-0.02	31.6	2.2	0.32	-6.22×10 ⁻³	2.52
Metal depletion (kgFe-eq)	153	138	0.25	291	216	162	-9.04	369	80.6	17.43	-3.93	94.1
Fossil depletion (kgOil-eq)	26.1	237	-1.2	261	77.2	277	-2.23	362	114	1225	-2.04	1337
Terrestrial acidification (kgSO ₂ -eq)	0.56	3.67	-2.64×10 ⁻²	4.2	1.52	4.3	-2.00×10 ⁻²	5.79	2.04	1.28	-0.02	3.3
Terrestrial ecotoxicity (kg1,4-DCB-eq)	0.025	0.18	0.28	0.49	0.059	0.21	0.29	0.56	0.0313	0.0145	2.53×10 ⁻³	0.0484
Marine eutrophication (kgN-eq)	0.15	1.07	-6.35×10 ⁻⁴	1.22	0.39	1.25	-6.88×10 ⁻³	1.63	0.57	0.4	-1.60×10 ⁻³	0.97
Marine ecotoxicity (kg1,4-DCB-eq)	36.3	182	112	330	51.4	213	-0.19	265	7.1	2.41	0.58	10.1
Freshwater eutrophication (kgP-eq)	0.1	0.27	-1.97×10 ⁻³	0.38	0.2	0.32	-4.22×10 ⁻³	0.52	0.1	0.015	-2.48×10 ⁻³	0.11
Freshwater ecotoxicity (kg-1,4-DCB-eq)	41.5	208	130	380	57.4	243	-0.17	301	7.64	1.57	0.70	9.91
Photochemical oxidant formation (kgNMVOC)	0.5	2.3	-7.81×10 ⁻³	2.78	1.08	2.68	-3.95×10 ⁻²	3.72	1.59	1.7	-0.02	3.27
Ionising radiation (kg6U235-eq)	5.75	5041	-0.1	5047	17.9	5906	-0.13	5924	10.49	5.15	-0.13	15.5
Particulate matter formation (kg-PM10-eq)	0.27	1.5	3.85×10 ⁻²	1.77	0.85	1.72	1.53×10 ⁻²	2.58	1.1	0.44	-0.02	1.52
Human toxicity (kg1,4-DCB-eq)	145	683	0.22	828	315	800.3	-2.46	1113	148	18.49	-1.56	164

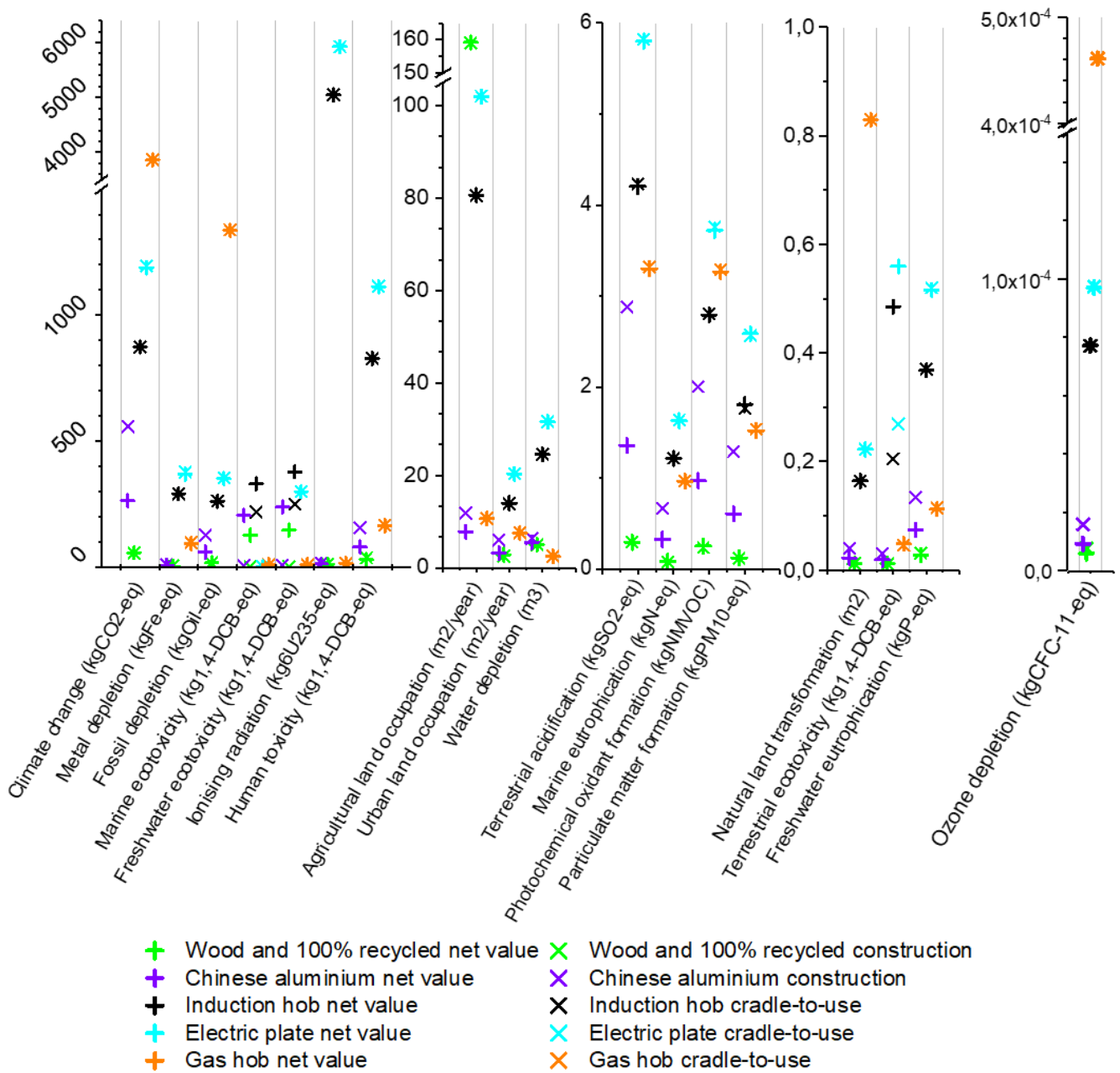


Figure 12: Net impacts and cradle to use mid-point impacts of the wood-100% recycled aluminium, the reference Chinese aluminium solar cookers and the conventional devices

4.3. Implications and limitations of the present study

4.3.1. Energy consumption devoted to cooking

The adequation of the chosen functional unit “to heat 2L of water from 25°C to 90°C three times a day, every day, during 40 years using the most adapted pot with lid” with respect to the energy consumption currently devoted to cooking is discussed herein. The theoretical annual consumption of *ca.* 165 kWh given by this functional unit divided by the efficiency

leads to the final energy consumptions in our model. It equals 223 kWh/year, 261 kWh/year and 320 kWh/year for the induction hob, electric plate and gas hob, respectively. Data from the French government indicates that the mean annual consumption of French households for cooking reaches 665 kWh/year, but this value includes all appliances (oven, kettle ...) [35]. When only the studied cooking device (induction hob or the electric plate or the gas hob) is considered, estimated values are in the range of 300-400 kWh/year [36]. Thus, the functional unit under-estimates the energy consumption by around a factor 2 compared to the energy devoted to cooking by western households. Given the large part of the environmental impacts due to the use phase for the standard appliances, this leads to an under-estimation, in the present work, of the standard appliances impacts compared to the solar cooker. Moreover, one should note that solar cookers can be used for providing hot water for baths or shower, saving additional emissions. These uses were however not considered in the functional unit.

4.3.2. The influence of life span hypotheses and wood transport

The life span value for each technology was chosen as a best guess. A change in the life span would modify significantly the results for the solar device since the construction phase is the only impact contributor. The raw data provided with the present article permits to recalculate the impacts with different hypotheses. For other devices, the construction phase represents at most 12% of the total impacts, therefore a change in their life span would not affect much their environmental impacts.

The model assumes that the wood pieces are manufactured close to the using site, without transportation. When the wood structure is transported from the assembly place of the parabola to the user, the impacts rise notably. For instance, for the wood and recycled aluminium device, the climate change and the fossil depletion indicators increase by 36% (from 56 kgCO_{2eq} to 76 kgCO_{2eq}) and 47% (from 16 kgOil_{eq} to 24 kgOil_{eq}), respectively. In term of end-points, the overall end-point indicator rises from 11 points to 14. However, even with such an increase, using wood for the structure is less impacting than the aluminium structure.

4.3.3. Influence of electricity mix on the climate change indicator

The use stage was considered located in France, where the electricity mix is dominated by the nuclear power and is relatively low-carbon (52 gCO_{2eq}/kWh in 2022 [37]). The results for the induction hob and the electric plate would thus be completely different in another country. To illustrate this point, Figure 13 shows the climate change impact of the induction hob with electricity mix values from Spain (468 gCO_{2eq}/kWh), Germany (657 gCO_{2eq}/kWh) and Australia (1.12 kgCO_{2eq}/kWh). In countries with CO₂-intensive electricity mixes, i) the construction phase becomes completely negligible compared to the use phase (*ca.* 1% in the case of Australia), and ii) the advantage of solar cooking increases dramatically. Even the reference solar cooker (Chinese aluminium) has CO₂ emissions 15 times lower than the induction hob used in Australia. For the solar cooker made of wood and recycled aluminium, the difference between the two reaches a factor 150. This shows that even a moderate use of the solar cooker is beneficial in countries with a CO₂-intensive electricity mix. In countries with a low-carbon mix, the advantages of solar cookers are clear if (i) they are intensively used or (ii) they are made of low-carbon materials: wood and/or low-carbon aluminium. This aspect is discussed in the next section.

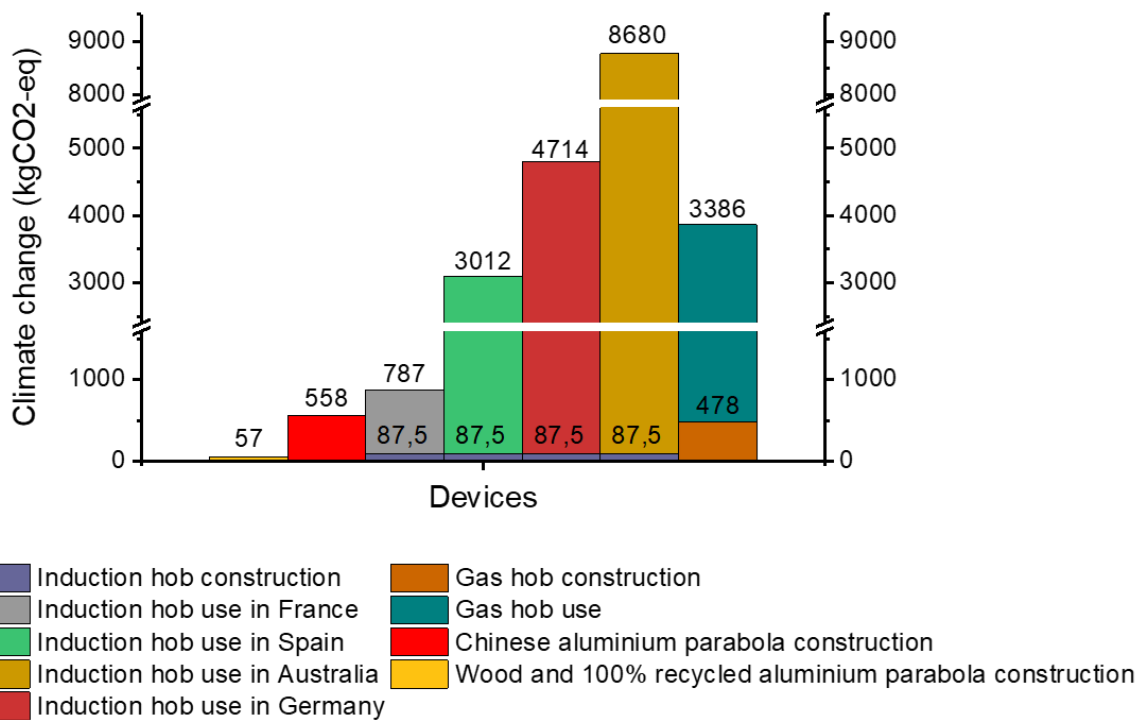


Figure 13: Climate change impact for the induction hob with electricity mix from France (grey), Spain (green), Germany (red) and Australia (yellow). The construction phase is also shown in blue. The indicated values correspond to the impact of each phase.

4.3.4. Conditions for climate benefits of solar cookers

The LCA results were compared for a 100% use of solar cooking vs 100% use of conventional cooking. In real life, owners of solar cookers also use at least one complementary standard appliance. This section determines the conditions for which it is worth buying a solar cooker to lower the climate impact. A simple calculation shows that, for the solar cooker to be more advantageous, the following condition must be met (see SI section F for details):

$$x > \frac{C_{solar}}{U_{standard}},$$

where x is the fraction of meal cooked with the solar device, C_{solar} is the climate change impact related to the construction phase of the solar cooker and $U_{standard}$ is the one related to the use of a standard cooking appliance.

Table 8 shows the x values calculated for solar cookers composed of different materials, for various types of appliances, and for different electricity mixes. The colours in the table corresponds to different ranges of use. In Toulouse (France), 45% of daytime are sunny. This means that, technically, x values above 45% cannot be reached. Corresponding cells were put in red into the table: in these cases (French electricity mix and high impact solar cookers), buying a solar cooker is not climatically beneficial. Cells for which $22.5\% < x < 45\%$ are orange. These are the cases where it makes sense to buy a solar cooker only if more than one meal out of two (during sunny days) are solar cooked. Green cells correspond to a very occasional use, which might be the case with a mainstream western lifestyle: we count only

two possible solar lunches per week (for instance in weekend), when sun is present. This corresponds to x values below 4.25%, or approximately one meal per week all over the year. Interestingly, even with such a loose use, it is worth buying a solar cooker in two cases: i) with a very CO₂-intensive electricity mix (Australian mix line in Table 8), or ii) if a low-impact parabola is bought and/or home-built (the two last columns of Table 8). Finally, yellow cells correspond to “committed users”, with $4.25\% < x < 22.5\%$, who will cook solar meals during the week.

Table 8: Percentage of the cooked meals above which a household reduces its climate change impacts when using a solar cooker. Use and construction emissions are expressed in kCO₂eq. The calculations have been performed for solar cookers composed of different materials, for various types of appliances, and for different electricity mixes. Colours correspond to different ranges of use: red for $x > 45\%$; orange for $22.5\% < x < 45\%$; yellow for $4.25\% < x < 22.5\%$; green for $x < 4.25\%$.

		Reference (SI Table D-1)	Wood and Chinese aluminium (SI Table D-3)	Chinses aluminium and 35% recycled (SI Table D-1)	Chinese aluminium with recycled (SI Table D-2)	Canadian aluminium (SI Table D-1)	100% recycled aluminium (SI Table D-1)	Wood and recycled aluminium (SI Table D- 3)
Construction emissions →		558	356	348	265	203	76	57
Use emissions ↓								
Induction hob, French mix (SI Table E-1)	760	73.4%	46.8%	45.8%	34.9%	26.7%	10.0%	7.5%
Electric plate, French mix (SI Table E-1)	903	61.8%	39.4%	38.5%	29.3%	22.5%	8.4%	6.3%
Induction hob, Spain mix	2908	19.2%	12.2%	12.0%	9.1%	7.0%	2.6%	2.0%
Gas hob (SI Table E-1)	3278	17.0%	10.9%	10.6%	8.1%	6.2%	2.3%	1.7%
Induction hob, Germain mix	4551	12.3%	7.8%	7.6%	5.8%	4.5%	1.7%	1.3%
Induction hob, Australian mix	8381	6.7%	4.2%	4.2%	3.2%	2.4%	0.9%	0.7%

5. Conclusions

A comparative LCA study was conducted for analysing the environmental performances of the conventional western cooking methods and of an alternative one. The inventory was built

upon the disassembly of these devices, manufacturer information, geographical localization and utilization performances. This study concludes on the following points:

- The origin of the aluminium has a large influence on the solar cooker impacts. Replacing the currently used Chinese aluminium by Canadian aluminium or recycled aluminium would decrease the mid-point impacts as well as the end-point final impact.
- The use of wood for the structure of the solar devices decreases most impacts but increases the agricultural land occupation indicator.
- The most impacting devices among the conventional ones in the mid-point approach is the electric plate or the gas hob, although on different categories for each of them. When aggregating the impact results in the end-point approach, the most damaging in France – which has a low-carbon electricity mix – is by far the gas hob, mostly due to the combustion of natural gas.
- Conventional devices always have larger impacts than the parabolic solar cookers, this trend being due to the energy consumption by the formers in their use phase. Considering only the construction phase, the conventional devices have impacts of the same order of magnitude or lower than the solar cookers.
- The end-of-life recycling decreases the overall impacts of the solar cookers for almost all indicators, except for freshwater and marine ecotoxicity due to the treatment of aluminium scrap. For the conventional devices, the end-of-life does not significantly influence the global end-point score and the majority of mid-point indicators. There are few exceptions: terrestrial, freshwater and marine ecotoxicity rise due to the treatment of scraps while metal depletion and particulate matter lower thanks to the avoided production of steel or aluminium.
- The present results have been obtained using the French electricity mix, *i.e.* a low-carbon electricity mainly of nuclear origin. The impacts of the electric plate and induction hob are completely modified using another electricity mix. For a CO₂-intensive electricity mix, the construction phase becomes negligible since the use phase leads to extremely large emissions compared to the solar cooker ones, and even to the gas hob one in some cases.
- A regular use of the solar cooker permits to reduce the impact, even when the high-impact reference solar cooker (100% Chinese aluminium) is bought. The only case where a solar cooker does not reduce the impacts is when the reference parabola is bought in complement of an electric device in a country with a low-carbon electricity mix. On the contrary, even with a very loose use (one solar meal per week), it is worth cooking on sun in countries with a very CO₂-intensive electricity mix and/or with a low-impact solar cooker.

The use of solar cooking is of course not accessible to everyone and notably to people living in apartment buildings, but it has a large potential of deployment for people living in enough space to accommodate it and with an easy access to the sunlight. Solar cooking has often been considered as a mean of cooking for people of the global South to replace wood cooking, however, changes in the life style in the North are possible with ecological benefits.

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Appendix:

The supplementary information document presents more detailed results. The raw data collected and calculated are available at <https://doi.org/10.48531/JBRU.CALMIP/GJHIIIH>.

Declaration of competing interest

None

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