Environmental impact analysis applied to solar pasteurization systems

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Nomenclature

$\dot{Ex}$	Exergy rate, J/s
$\dot{m}$	Mass flow rate, kg/s
h	Specific enthalpy, J/kg
T	Temperature, K

s	Specific entropy, J/(kg*K)
$\dot{B}$	Environmental impact rate of an energy stream, points/s (ReCiPe 2008)
B	Environmental impact of an energy stream, points/d (ReCiPe 2008)
b	Specific environmental impact, points/J (ReCiPe 2008)
$\dot{Y}$	Component-related environmental impact rate associated with the life cycle of the component, points/s (ReCiPe 2008)
Y	Component-related environmental impact associated with the life cycle of the component, points/d (ReCiPe 2008)
f	Exergo-environmental factor, non-dimensional
A	Surface of the solar collector, m^2
ab	Inhabitants
d	Days
h	Hours
NCS	Natural Circulation System
NCS_80	Natural Circulation System with a productivity of the 80%
NCS_eq	Natural Circulation System with an equivalent productivity to the Thermostatic Valve System
NCS_Italy	Natural Circulation System installed in Italy
NCS_Brazil	Natural Circulation System installed in Brazil
NCS_Somalia	Natural Circulation System installed in Somalia

TVS	Thermostatic Valve System
TVS_Italy	Thermostatic Valve System installed in Italy
TVS_Brazil	Thermostatic Valve System installed in Brazil
TVS_Somalia	Thermostatic Valve System installed in Somalia
PTC	Parabolic Trough Concentrator
SC	Solar Collector
CT	Compensation Tank
PV	Photovoltaic
HE	Heat Exchanger
TV	Thermostatic Valve
WT	Water Tank

Subscripts

0	Relative to the environment
j	Relative to the j-th flow
k	Relative to the k-th component
D	Destructions
F	Exergetic fuel
P	Exergetic product

in	Relative to an inlet flow in a component
out	Relative to an outlet flow from a component
TOT	Relative to a total amount
80	Referred to the 80% of ideal productivity
eq	Referred to an equivalent productivity of both systems
Italy	Referred to the case of Italy as installation site
Brazil	Referred to the case of Brazil as installation site
Somalia	Referred to the case of Somalia as installation site

Superscripts

CO	Relative to the construction phase of a component
OM	Relative to the operation and maintenance phase of a component
DI	Relative to the disposal phase of a component

Greek symbols

Δ	Variation

Abstract

In many under-developed regions of the world, most people live in rural villages, where the electrical grid is often not available and traditional potabilization systems would be too expensive and technologically too complex to be implemented. Thus every year, millions of people in the world die due to diseases related to water contamination. Solar Pasteurization Systems represents a promising alternative to address such problems, as they can thermally disinfect water employing solar energy alone, without using fossil fuels or electrical grid connection. Evaluating the cradle-to-grave environmental footprint of Solar Pasteurization Systems, and in general of technologies aimed at producing safe drinking water, represents an issue of major importance. This is relevant because an effective solution has to be, at the same time, environmentally and locally sustainable for a given geographical context. In this work, a complete Life Cycle Assessment and Exergo-environmental analysis are performed in order to calculate and compare the eco-profiles of two Solar Pasteurization technologies: a Natural Circulation and a Thermostatic Valve System. Results show that Natural Circulations Systems are generally more environmentally sustainable (0.30 mPt/l) than the Thermostatic Valve System (0.83 mPt/l) thanks to the higher productivity of treated water. A sensitivity analysis is performed to investigate the dependency of the model systems from different operational and environmental conditions, at different installation sites, i.e. Somalia, Brazil and Italy. The main difference is represented by the productivity of the systems. In all cases the solar collector array is the main item responsible for environmental burdens, impacting for almost 45% of the total score. The analysis also shows that the use of solar energy in Pasteurization is important to avoid direct emissions and to lower the global environmental impact connected with thermal energy production compared to the eco-profiles of other widely diffused pasteurization technologies based on the combustion of fossil fuels or biomass that can be used to provide the same function (in general higher than 1.2 mPt/l). Moreover, with the aim of qualitatively assessing the benefit associated with the potential implementation of solar pasteurization systems, an improvement of the sanitary conditions is envisioned, especially in under-developed countries where, definitively, a large scale diffusion would be recommended.

Keywords: Solar Pasteurization, Solar Energy, Life Cycle Assessment, Exergo-environmental analysis, Water Treatment, Water Disinfection.

1. Introduction

According to UNICEF and World Health Organization (UNICEF and WHO, 2009) diarrhoeal diseases are the second major reason of mortality of children under five years old, killing around 1.5 million of them every year. This situation is extremely aggravated in Africa, where the mortality rate due to unsafe water, hygiene and sanitation services is triple that of the global rate; e.g., in Somalia, more than 60,000 cases of suspected cholera have been reported between January and August 2017 and more than 800 people have died (World Health Organization (WHO) (accessed on 05/04/2018)). Indeed, Somalia is one of the most affected countries by such sanitary disaster related to unsafe water, probably the main vector of cholera's pathogens and many other diseases.

Among technologies that can be applied (Shannon et al., 2008) to avoid or limit drinking water contamination, Solar Pasteurization Systems are rather cheap and simple plants able to disinfect water by employing solar energy. Two different Solar Pasteurization Systems are available: The Natural circulation systems (NCSs) and Thermostatic valve systems (TVSs).

The first NCS system was proposed by Boettcher et al. (1983) in which the only driving force of the fluid is the variation of its density induced by solar energy. The volumetric expansion is used to separate treated and untreated water thanks to a well-dimensioned system of pipes. Then Bansal et al. (1988) built and tested a density driven system with an evacuated tubes SC in order to estimate its energetic performances. Ten years later, Cobb (1998) investigated a simple Pasteurization System composed of two concentric copper pipes with a productivity of 7.5 l/h-m^2.

With the aim of improving the NCS's performance, several implementations have been proposed. Duff and Hodgson (2001) built and tested a simple NCS prototype composed of a collector tube and a riser tube. The water in the riser tube is not warmed by the solar radiation and even if the fluid inside the collector tube reaches the required temperature, it impedes the natural circulation and the water inside the collector continues warming up until it boils. To avoid such problem, they introduced an internal loop ensuring that the temperature of the water in the riser tube is always close to the temperature inside the collector (Duff and Hodgson, 2002). Taking inspiration from Duff and Hodgson's idea, Dainelli et al. (2017) and Manfrida et al. (2017) studied a new NCS system (**Fig. 1**) working as follows: untreated water flows through the makeup pipe from the supply water tank to a regenerative heat exchanger (HE) where it is preheated by the outlet water. Afterwards, inside the circuit, the inlet water flows across a compensation tank (CT) and enters a solar collectors (SCs) array where it is warmed by solar radiation. The concomitant volume increase ensures that the water flows across the riser pipe and, thanks to the difference of volume, enters the holding pipe where, only if the temperature is ≥85° (enough to kill or inactivate pathogens almost instantly (Burch and Thomas, 1998)), the thermal expansion is sufficient to allow water reaching the treated water tank through the discharge pipe. In that case, the outlet flux is replaced by the same mass of raw water because of the communicating vessels principle. The down-comer pipe brings in the non-overtopped water to close the loop. The mixture of inflow and circulating water goes around the pipes system until a low level of solar radiation causes the flow to stop.

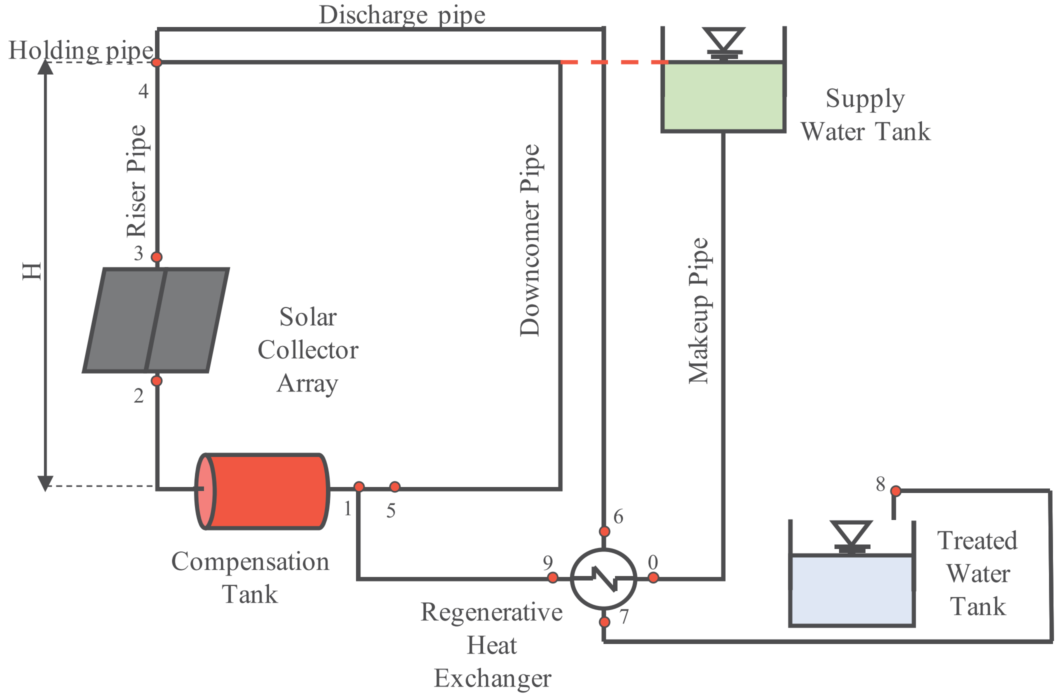


Fig. 1: NCS technical configuration and representative points of the plant (adapted from Manfrida et al. 2017). (0 = inlet cold water flow inside HE; 1= inlet flow inside the circuit; 2= inlet water inside the SCs; 3= outlet water inside the SCs; 4= outlet water from riser pipe; 5= end of the circuit; 6= inlet hot water flow inside the HE; 7= outlet hot water flow from the HE; 8= Inlet water to treated WT; 9= outlet cold water from HE).

The NCS developed by Manfrida et al. (2017) is sized to warm water up to 85°C and its productivity is estimated using a mathematical model of the thermo-hydraulics of the system in off-design conditions. Based on the same mathematical model for the estimation of system performances, Dainelli and co-workers performed an exergy analysis and the results were applied for an exergo-economic study of the system (Dainelli et al., 2017).

Duff and Hodgson (Duff and Hodgson, 2005) also reviewed the studies related to the TVSs. In a TVS, the presence of an electronic control device, composed of thermostatic valves and time and temperature sensors, allows the setting of the disinfection conditions for treated water. Thus, contrarily to NCSs, TVSs face the problem of obsolescence and malfunctioning of the thermostatic valves (Duff and Hodgson, 2005) that, as every electronic device, can be damaged. The TVS simplest scheme consists of a flat plate SC between two reservoirs with a thermostatic valve (TV) to regulate the flow of water (Jorgensen, A.J., Nohr, K., Sorensen, H., Boisen, 1998), its productivity was estimated to 50 l/m^2-d. The introduction of a HE to preheat the inlet raw water, improved this value obtaining up to 55 l/h-m^2 as described in the study of Stevens et al. (1998) and up to 205 l/h-m^2 as estimated by Safe Water Systems (2002). A Solar Pasteurization System with a parabolic trough concentrator (PTC), which is estimated to produce 89.3 l/m^2-day of drinking water, has been used by Anderson (1996); after several years Bigoni et al., (2014) tested a very similar PTC Pasteurization plant in order to analyse the efficiency of water disinfection. A prototype of an automated Pasteurization System regulated by TVs has been built, tested and optimised by Carielo da Silva et al. (2016) and Carielo et al. (2017). The layout of the system shown in **Fig. 2** is composed of a flat plate SC, a HE, two water tanks (WTs) and a 10 W photovoltaic (PV) panel to provide energy to the electric parts. The system was made operative from 7:00 a.m. to 4:00 p.m. and a control algorithm was implemented so that five set-point conditions are defined: 55°C/3600 s, 60°C/2700 s, 65°C/1800 s, 75°C/900 s and 85°C/15 s.

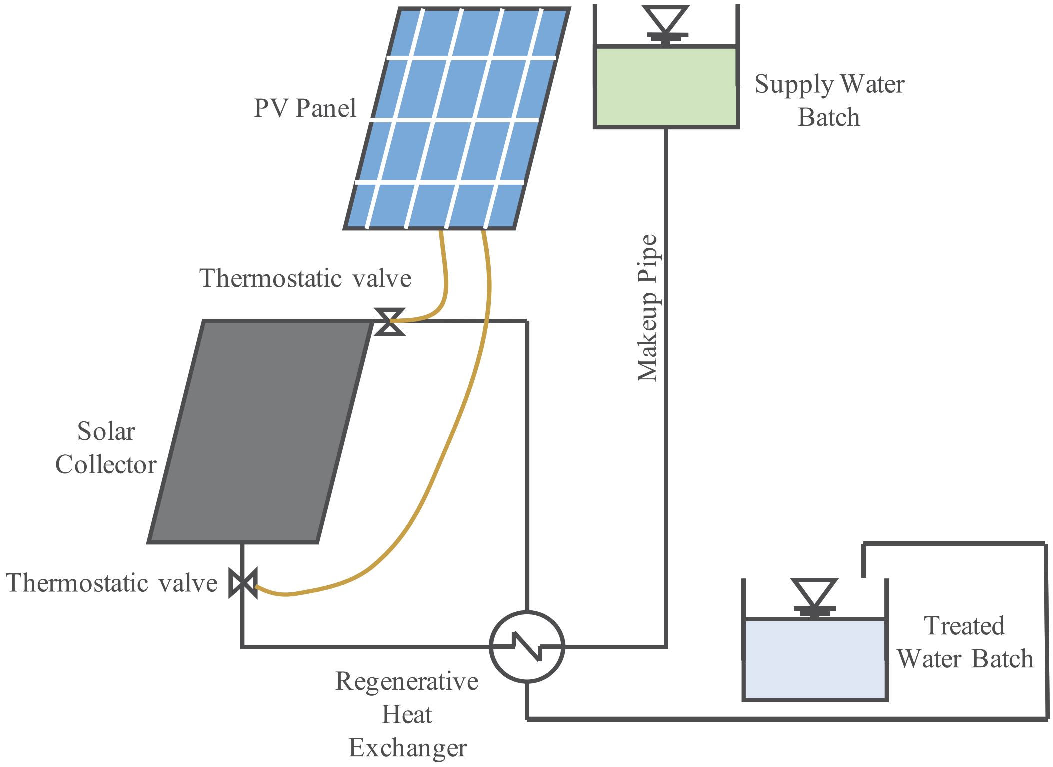


Fig. 2: TVS technical configuration (adapted from Carielo et al., 2017).

A linear regression (**Fig. 3**) correlated its productivity, expressed as number of refilled batches (vessels with 2 litres of capacity), with solar irradiation in order to estimate the performances of the system in each moment of the year and all over the world (Carielo et al., 2017).

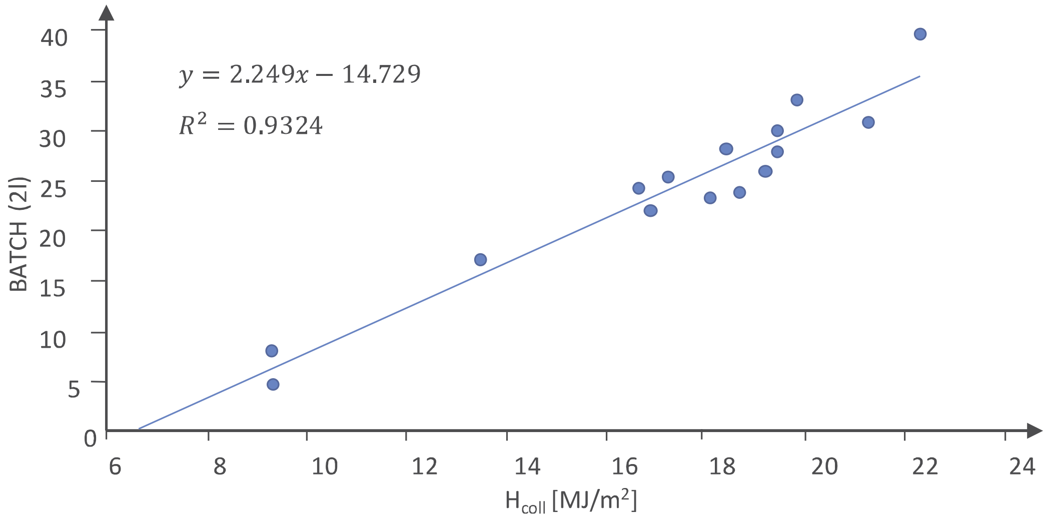


Fig. 3: TVS productivity (refilled batches, i.e. 2 litres vessels) as function of the solar irradiance (adapted from Carielo et al., 2017).

Although a complete potabilization would require the removal of suspended and dissolved contaminants by physical or biological treatments, the NCSs and TVSs can be still used to disinfect water in rural villages where pathogens are the most relevant problem. Indeed, they are responsible for so many victims and their elimination represents the most critical issue for sanitation. Furthermore, physical and biological plants would require a massive consumption of electricity, the employment of expensive chemicals and onerous maintenance.

Thus, taking into account that rural areas are often very poor and unachievable by the electrical grid and transports, these technologies cannot be reliable and a Solar Pasteurization System can represent a suitable and affordable solution in that particular context.

As clarified in the introduction, the performances of the NCSs and the TVSs have been already discussed in several literature papers but none of them encompasses the whole life cycle of the system with an environmental, resource or energy consumption perspective approach. Evaluating the eco-profile of Solar Pasteurization Systems, and in general of technologies aimed at producing safe drinking water, represents an issue of major importance. This is relevant because an effective solution must be, at the same time, environmentally and locally sustainable for a given geographical context. The latter issue is particularly important to contribute to an integrated assessment envisioning the environmental, social and economic dimensions on topics related to water's sanitation and hygiene (Tilley et al., 2014) (Murphy et al., 2009). Such a comprehensive approach is well within the directives of the United Nations (UN) collected in the Agenda for Sustainable Development (United Nations, 2015) (United Nations, 2016) (United Nations, 2017). Indeed, among the 17 Sustainable Development Goals (SDGs), the mission of Goal 6 is precisely to "Ensure availability and sustainable management of water and sanitation for all". In this context, water research and development is strongly encouraged (United Nations, 2016). However, the present study could also contribute to reach the objectives of other SDGs concerning poverty, food and energy matters (e.g., SDG 7: "Ensure access to affordable, reliable, sustainable and modern energy for all").

The aim of this study is to apply the Life Cycle Assessment (LCA) and exergo-environmental methodology to estimate the potential environmental advantages connected with the use of Solar Pasteurization. The LCA is a powerful methodology to assess the potential environmental impacts connected with a product system embracing all raw materials and energy flows involved in its life cycle from a quantitative point of view. The exergo-environmental analysis is a very useful tool integrating the quantitative approach of LCA with qualitative aspects. Exergy is defined as the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir (Perrot, 1998) and for such reason it is considered as an indicator of the quality of energy

Indeed, the quality of the energy flows, represented by the exergy content of water, decreases because of the thermodynamic irreversibility. Thus, the goal of the exergo-environmental analysis is to assess how this unavoidable problem affects the environmental performance of systems which mainly work with thermal energy The LCA approach has already been successfully applied to compare conventional and alternative non-solar Pasteurization Systems of tomato and watermelon juice (Aganovic et al., 2017). An exergy analysis has been performed on a milk processing plant, that also includes a pasteurization system, but no exergo-environmental analysis was implemented as a further investigation (Mojarab Soufiyan et al., 2016). Thus, the application of exergo-environmental analysis to pasteurization system represents an innovative approach. In this study the environmental footprint of the NCS system described by Dainelli et al. (2017) and Manfrida et al. (2017) is calculated and compared to that of the TVS system reported in Carielo da Silva et al. (2016) and Carielo et al. (2017). The evaluation of the dependency of the NCS and TVS eco-profiles on geographical boundaries have been performed through a sensitivity analysis considering different installation sites. Moreover, as both NCS and TVS are powered by solar energy only, to evaluate the environmental benefit associated with a renewable source of energy, a comparison is performed with other technologies based on the combustion of fossil fuels or biomass employed to provide the same amount of thermal energy to heat water. Indeed, the literature provides several examples about how the use of a non renewable source of energy in traditional plants determines high environmental footprints for traditional pasteurization systems (Pardo and Zufía, 2012), especially concerning the global warming and energy depletion categories (Li et al., 2018). Finally, to further investigate the potential of Solar Pasteurization, we perform a qualitative assessment of the potential benefits concerning the human health issue that could be achieved with the implementation of solar pasteurization systems in under-developed countries.

Such results would allow for improved knowledge about available solutions to guarantee potable water supply and thus could contribute to inform and support in choosing the best options for a specific geographical context.

2. Methodological approach

Life Cycle Assessment (LCA) is a very useful methodology to investigate and quantify the environmental impacts connected to a product, process or service system. In this work, an LCA study is presented according to the ISO 14040 (International Standards Organization 2010) and ISO 14044 (The International Standards Organisation 2006), regulations that standardize the method that is composed of four phases:

- *Definition of the goal and scope of the system*: includes the description of the model system and its borders, along with the methodological framework;
- *Life Cycle Inventory, LCI*: lists and quantifies all the inlet and outlet flows of energy and materials and releases to the environment;
- *Life Cycle Impact Assessment, LCIA*: impacts generated by the system are assessed through the application of an impact calculation method that translate emissions, resources and energy use into a limited number of environmental indicators;
- *Life Cycle Interpretation*: technical findings and critical points identified through the analysis are employed to outline recommendations and conclusions to improve the sustainability of the system and choosing the best available alternative.

Calculations have been performed with the open source software OpenLCA version 1.7 (developed by Greendelta). As no prototypes for the NCS and TVS are available and, thus, no primary data could be collected, their analytical models were built considering the configurations described in Dainelli et al. (2017), Manfrida et al. (2017) and Carielo da Silva et al. (2016), Carielo et al. (2017), respectively. Secondary data are taken from the database Ecoinvent 3.4, customized when necessary.

2.1. Definition of the goal and scope of the system

The boundaries of the systems are defined according to a cradle-to-grave approach, including production, operation and disposal phases as represented in **Fig. 4**:

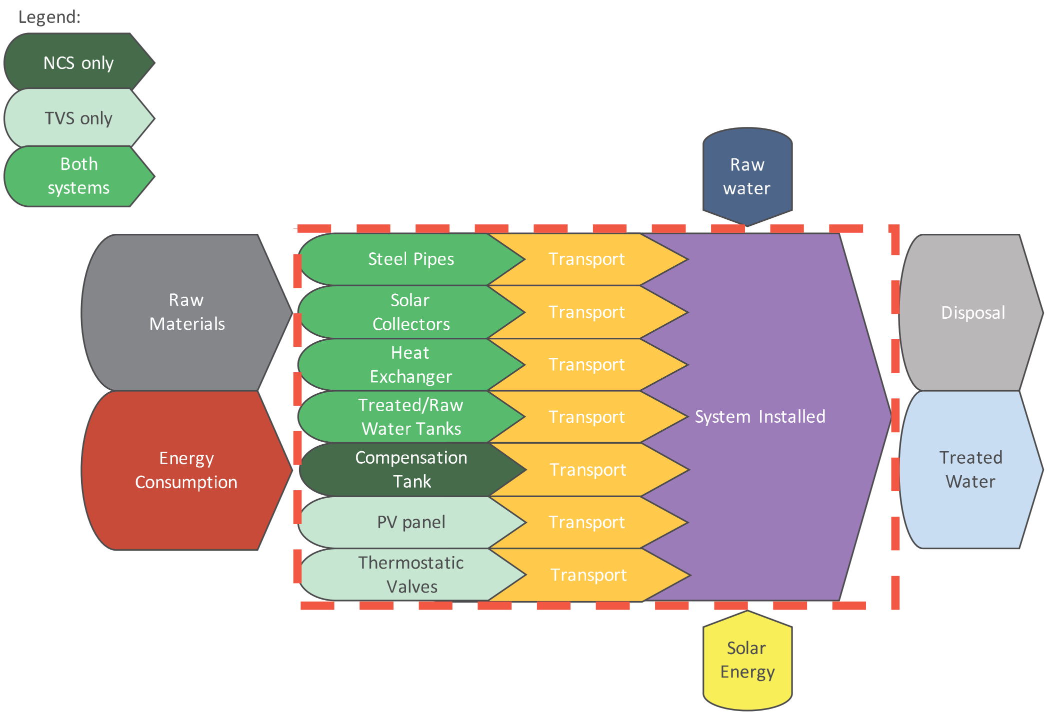


Fig. 4: System boundaries of the solar pasteurization systems considered in this study. Green boxes are referred to common systems components, dark green box refers to the NCS and light green to TVS only.

As already stated in the introduction, the goal of the present analysis is to evaluate and compare the environmental performances of the NCS and TVS systems. The functional unit is defined as 1 litre of treated water. In more detail, the study aims to: (i) compare the environmental footprints of solar pasteurization systems in three different locations and to point out the most sustainable solution; (ii) point out the most impactful components and processes involved in the systems; and (iii) evaluate the potential advantages connected with the implementation of Solar Pasteurization Systems respect to the effect of diseases connected with the consumption of unsafe water in the three different geographical context. Concerning these last, the following installation sites have been considered:

- Somalia: a country most affected by diarrhoeal diseases, as highlighted in the introduction;

- Brazil: the country where Carielo da Silva et al. (2016) and Carielo et al. (2017) built and tested the system;
- Italy: one of the countries where Dainelli et al. (2017) and Manfrida et al. (2017) simulated their Solar Pasteurization System.

2.2. LCI

In the framework of LCI, all processes included within the system boundaries are modelled as operational units: for each one of these inlet and outlet flows of matter and energy, environmental releases to the atmosphere, ground and water compartments are accounted. Detailed LCIs for the systems investigated in this study are provided in the supporting information. (SI, section 1). Data collected for the LCI analysis of the components are reported in **Table 1**.

Table 1: LCI of the systems.

Components	**NCS**		**TVS**	
	n° of items	Description	n° of items	Description
Solar collectors (SCs)	2	flat plate evacuated tube SCs with a surface of 1.95 m^2 (VPsolar (accessed on 05/04/2018)).	2	Flat plate SC with a copper absorber and a surface of 1.34 m^2 (Heliotek Bosch Group (accessed on 05/04/2018)).
Compensation Tank (CT)	1	expansion vessel with volume 80l.	-	

Heat Exchangers (HEs)	1	pipe-in-pipe Heat Exchanger composed of steel pipes and rockwool thermal insulation.	1	Heat exchanger composed of a copper conductive part, rockwool insulation and an external iron box (Carielo da Silva et al., 2016),(Carielo et al., 2017).
Water Tanks (WTs)	2	Polyethylene tanks for inlet and outlet water.	2	Polyethylene tanks for inlet and outlet water.
Photovoltaic (PV) panels		-	1	PV panel with nominal rated power equal to 10 W (Carielo da Silva et al., 2016),(Carielo et al., 2017)
Thermostatic valves (TVs)		-	6	Electronic control devices with 6 years operative life.
Wires		-	-	bipolar copper wire with a length of 7 m (estimated from the arrangement in. Carielo et al., 2017).

2.2.1. Transportation

The transportation of the components of the plant can be at the origin of a substantial impact. Jorgensen and Ywema (Jorgensen and Ywema, 1996) focus on the relevance but also on the variability of transportation contribution to the LCA of a product, underlining that is noteworthy to estimate how influencing the transportation parameters (mass of the products, which is set by the physical properties of the components, distances and modes of transport, which vary depending on the starting and arriving points, etc) can affect the results of the analysis. As a definite fabrication site does not exist for the NCS and TVS in this study, an average of all the production and transportation processes connected with the same reference flow characterizing the various components is considered. To take into account the sensitivity of the results to transportation distances and modes, a common starting point is set in Milan and the installation sites are supposed to be rural villages 130 km distant from the nearest city centre and, in particular:

- for Somalia, the components are transported to Ancona port by an EURO6 lorry (about 400 km), to Mogadishu by boat (about 9800 km) and finally to the installation site by an EURO3 lorry (130 km);
- for Brazil, the components are transported to Lisbon by rail (about 2100 km), to Recife by boat (about 5800 km) and finally to the installation site by an EURO3 lorry (130 km);
- for Italy, the components are transported to the installation site near Brindisi by an EURO6 lorry (about 1100 km).

Such a transportation system is schematically represented in **Fig. 5**

Fig. 5 Sketch of the transportation routes and modes.

2.2.2. Installation and maintenance

The installation and maintenance phases of the investigated systems do not require complex procedures nor material nor energy consuming processes (Dainelli et al., 2017) thus their contribution to the analysis has been neglected. The same assumption applies for human labour because, considering the use of plug-and-play components allowing for an easy set-up of the NCS and TVS without the need for qualified operators, its contribution to the total environmental impact would be quite low. On the other hand, the direct occupation and transformation of land connected with systems' installation have been taken into account and evaluated according to an estimation of the area occupied by the plants (**Table 2**).

Table 2: LCI of the system's installation.

Components	Representative Dimension	NCS	TVS
Direct Land Occupation [$m^2 \cdot a$]	Surface Time	210	163.8
Direct Land Transformation [m^2]	Surface	17.8	10.92

For each installation site, the types of landscape considered are:

- Somalia: pasture and meadow as it covers most of the Somalian territory (Hadden and Lee, 2007);
- Brazil (Pernambuco): equatorial forest;
- Italy (Puglia): agricultural landscape.

2.2.3. Operative phase

The operative life of the two systems, defined as the period of time during which they work to produce drinking water, is considered to be fifteen years (Dainelli et al., 2017). The thermostatic valves included in TVSs have a shorter service life, assumed about six years, thus it is necessary to consider their replacement for at least three times during the whole TVS life cycle, for a total of six valves employed.

Concerning the production of drinking water, for the NCS case, the volume produced is estimated using the numerical model developed by Dainelli et al. (2017) and Manfrida et al. (2017); the performances of the TVS are evaluated using the linear regression relation defined by Carielo et al., (2017). The meteorological data are provided by the Meteonorm libraries ([dataset] Meteonorm Information (accessed on 05/04/2018)) and simulated using the software TRNSYS16 (developed by The University of Wisconsin Madison).

The volume of drinking water produced by the NCS and TVS is reported in **Table 3**. The productivity of the NCS is provided by a mathematical model and has not been validated by experimental tests. The model is based on thermodynamics equations and does not consider that, in real operative conditions, many unpredictable factors could lower the productivity (for instance the growth of seaweeds or the sedimentation of solids inside the pipes). Thus, values reported in **Table 3** represent the maximum productivity of the system in ideal conditions. To further investigate the environmental performance of the Solar Pasteurization Systems, two more uncertainty scenarios are analysed: in the first one, a load loss of 20% is assumed (NCS_80) and in the latter the two systems are considered to have the same yearly productivity (NCS_eq).

Table 3: Drinking water productivity for one year of the system.

Location	**Production [l/year]**	
	NCS	**TVS**
Somalia	75,718	20,562
Brazil	87,935	23,011
Italy	28,342	16,783

2.2.4. End-of-Life-phase

Concerning the end-of-life phase, it should be noticed that waste management strategies are very different depending on the countries where the installation sites are set and characterized by variable average recycling rates. In particular:

- Somalia: in under-developed countries waste management options are basically reduced to waste collection without any further treatment, thus no recycling or recovering processes have been taken into account and all the components are supposed to be landfilled;
- Brazil: an average recycling percentage has been set according to [dataset] Waste TM (accessed on 05/04/2018); the remaining part is supposed to be landfilled;
- Italy: an average recycling percentage has been set according to [dataset] Eurostat-waste (accessed on 05/04/2018) , the remaining part is supposed to be landfilled;

According to these considerations, the recycling rates reported in **Table 4** have been implemented in the model:

Table 4: Recycling rate by installation site.

Location	Somalia	Brazil	Italy
Recycling Rate	0.00 %	1.00%	45.1%

2.3. LCIA

After having collected all the energy and raw materials flows which enter and exit the system, the LCIA phase allows the calculation of the eco-profile of the systems according to several environmental impact categories. To this aim, various calculation methods are available.

In this study the *ReCiPe 2008, Endpoint (H) [v1.11, December 2014]* method, composed by 17 impact categories, is applied to perform the analysis. As the purpose of this paper is to provide results as general as possible, a hierarchist approach is selected. Endpoint results estimate the damages to the environment of a process or a product grouping them into issues of concern (damage-oriented approach) while midpoint ones express a measurement of effect before damage occurs (problem-oriented approach).

The classification of Endpoint results considers three damage categories:

- *Ecosystem*: damage to ecosystems is expressed as number of natural species lost per year (*species/year*);
- *Human Health*: damage to humans is expressed as *disability-adjusted life year* (*DALY*);
- *Resources*: damage to natural resources is expressed as the economic value in dollars of exploitation (*$*).

Normalisation and weighting are applied *(World ReCiPe H/A [person/year])* in order to express the impact into points allowing for a global comparison among different systems.

2.4. Energy and Exergo-environmental analysis

The comparison among NCS and TVS and conventional pasteurization systems is performed to assess the advantages associated with the use of solar energy for water heating. The environmental burden related to the conventional technologies (boilers burning oil, gas, or wood) has been estimated using secondary data from the database Ecoinvent 3.4, ("Ecoinvent," https://www.ecoinvent.org/). Oil is burned in a traditional 10 kW boiler for residential applications; all energy and material flows involved during its life cycle are provided directly by the producers. The same technology is applied to the natural gas combustion as Ecoinvent assumes that the same material and energy flows are involved in the production of oil boilers with similar size. Mixed logs are burned in a furnace developed in Switzerland and considered by Ecoinvent as the average technology for domestic applications. These processes are also inclusive of all the required ancillary technologies, such as fuel storage systems and electronic control devices.

In Solar Pasteurization Systems, water is warmed up to 85°C and has a sensible energy and exergy content that allows it to be considered as an energy carrier. In the analysed system, the exergy content of water is different in each point of the plant. For such reason the following equations are evaluated at representative points of the plant (**Fig. 1)** indicated by the subscript "j". Considering the environmental conditions as the reference and water as a non-reactive species, the exergy rate of the j-flow $\dot{Ex}_j$ (J/s) can be evaluated by Eq.1:

$$\dot{Ex}_j = \dot{m}_j[(h_j - h_0) - T_0(s_j - s_0)] \quad (1)$$

Where $\dot{m}_j$, h_j and s_j are respectively the water mass flow rate (kg/s), the specific enthalpy (J/kg) and the specific entropy (J/(kg*K)) related to the j-th flow; h_0, T_0 and s_0 are the specific enthalpy (J/kg), the temperature (K) and the specific entropy (J/(kg*K)) of the environment.

We see that temperature rise of water inside the SCs represents an increase of exergy, and thus a quality improvement but it has a cost in terms of environmental impact.

Thus, a damage can be allocated to the exergy content of water applying the definition of specific impact rate (Buchgeister, 2010) b_j (points/J):

$$b_j = \frac{\dot{B}_j}{\dot{E}x_j} \tag{2}$$

Where $\dot{B}_j$ is the environmental impact rate of j-th flow (points/s).

On the other hand, the environmental impact rate related to the construction, operation and maintenance and the disposal of the k-component of a system is evaluated by Eq.3 (Buchgeister, 2010):

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \tag{3}$$

Where $\dot{Y}_k$ is the total environmental impact rate associated with the life cycle of the k-th component (points/s) while $\dot{Y}_k^{CO}, \dot{Y}_k^{OM}$ and $\dot{Y}_k^{DI}$ are the contributions of the construction, the operation and maintenance and disposal phase (points/s).

The Exergo-environmental analysis is based on the impact balances for each entering and exiting *j*-flow related to each *k*-component (Buchgeister, 2010):

$$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out} \tag{4}$$

Where $\dot{B}_{k,in}$ are the environmental impact rates related to all the flows entering the k-th component (points/s) and $\dot{B}_{k,out}$ are the environmental impact rates related to all the flows exiting from the k-th component (points/s).

An exergy analysis of a NCS has been performed by Manfrida et al. (2017) estimating the exergy content of water in each point of the plant, and $\dot{Y}_k$ is provided by the LCA analysis (a mass based allocation approach has been used for the calculation of the environmental impacts of transports, packaging and direct land occupation for all the system components). These inputs permit us to solve the system of equations in integral form referring to the average day of each month.

Furthermore, inside each component, several exergy destructions occur: they are due to different forms of irreversibility such as non-ideal mixing of fluids, heat exchanges with finite difference of temperature and frictions across the pipes. An environmental impact $\dot{B}_{D,k}$ (points/s) can be associated to them because they vanquish part of such costly increasing exergy and it is calculated by Eq.5 (Buchgeister, 2010; Buchgeister et al., 2009):

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}x_{D,k} \tag{5}$$

Where $b_{F,k}$ is the specific environmental impact related to the exergetic fuel (Lazzaretto and Tsatsaronis, 2006) of the k-th component.

So, the total environmental impact for each k-component $\dot{B}_{TOT,k}$ is obtained by Eq.6 while the contribution of $\dot{Y}_k$ respect to $\dot{B}_{TOT,k}$ is named exergo-environmental factor ($f_{d,k}$) and is defined by Eq.7. The relative environmental impact difference $r_{d,k}$ is another parameter expressing, as percentage, how much the environmental cost of a water stream is increased by flowing across each component and it is defined by Eq.8 (Buchgeister, 2010; Buchgeister et al., 2009).

$$\dot{B}_{TOT,k} = \dot{B}_{D,k} + \dot{Y}_k \tag{6}$$

$$f_{d,k} = \frac{\dot{Y}_k}{\dot{B}_{D,k} + \dot{Y}_k} \quad (7)$$

$$r_{d,k} = \frac{b_{p,k} - b_{F,k}}{b_{F,k}} \quad (8)$$

3. Results and discussions

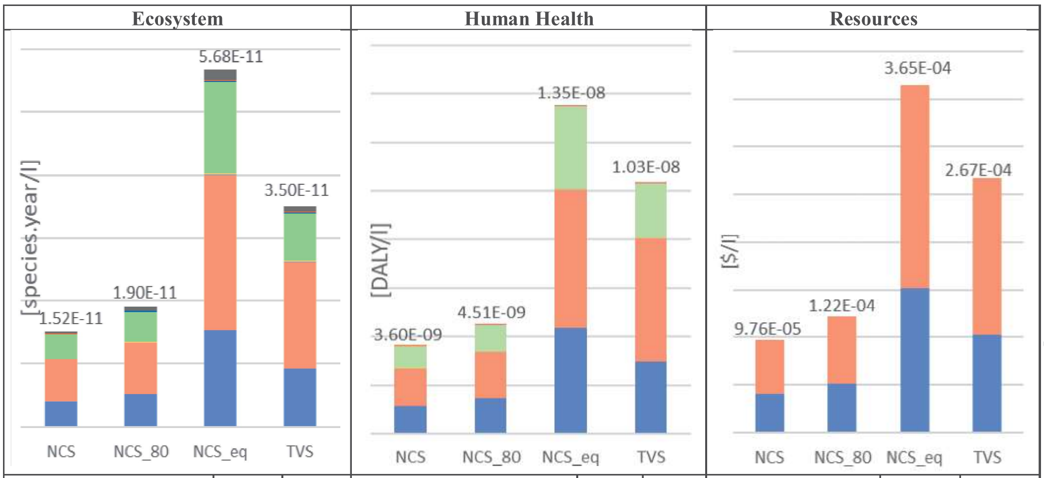
In this paragraph, the description of results is organized as follows:

- In Section 3.1, the endpoint results and contribution analysis of both NCS and TVS for Somalia, (i.e., the country with the most critical sanitary situation related to diarrhoeal diseases among the three investigated installation sites) are reported;
- In Section 3.2, the total environmental impact profiles for Somalia and, for comparison, for Brazil and Italy are reported;
- In Section 3.3 and 3.4, the energy, exergo-environmental results and sensitivity analysis outcomes for Somalia are reported.

3.1. Endpoint results and contribution analysis - Somalia

Fig. 6 shows the endpoint results for the NCS, NCS_80, NCS_eq and TVS in Somalia. The NCS system turns out to be the most sustainable solution for each category thanks to its higher productivity of treated water, even if a higher amount of materials is required. Furthermore, for each damage category, some major environmental burden can be identified. More in details, the *Agricultural land occupation and Climate Change* impact categories represent together about 70% of the contribution to the *Ecosystem*; the *Climate Change, Human Toxicity and Particulate matter* *formation* impact categories represent together more than 99% of the contribution to the *Human Health*; and finally the *Metal depletion impact category* represents about 60% of the contribution to the *Resources*.

Fig. 6 also shows that the productivity is a pivotal parameter for the NCS: if it is decreased of 20% with respect to ideal conditions (NCS_80) the environmental burden on all the damage categories increases but it is still lower than the TVS profile, while in the case of equivalent productivity of the two plants (NCS_eq), the resulting NCS environmental burden would turn out to be higher than TVS. This last outcome clearly depends on the larger amount of materials required for the NCS's construction but it cannot be considered as a drawback for the NCS as this equal productivity limiting case represents the worst scenario for NCS and it has been simulated to understand the sensitivity of the model (NCS productivity has been assessed through a mathematical model and the productivity of the TSV has been measured experimentally).



Categories	NCS	TVS
Agricultural land occupation	26.87%	26.33%
Climate Change	44.41%	47.98%
Freshwater ecotoxicity	0.30%	0.37%
Freshwater eutrophication	0.32%	0.46%
Marine ecotoxicity	0.06%	0.08%
Natural land transformation	24.41%	21.57%
Terrestrial acidification	0.28%	0.35%
Terrestrial ecotoxicity	0.35%	0.39%
Urban land occupation	2.99%	2.48%

Categories	NCS	TVS
Climate Change	32.29%	28.79%
Human Toxicity	42.34%	49.23%
Ionising Radiation	0.03%	0.03%
Ozone Depletion	0.01%	0.01%
Particulate matter formation	25.33%	21.95%
Photochemical oxidant formation	0.00%	0.00%

Categories	NCS	TVS
Fossil Depletion	41.69%	38.34%
Metal Depletion	58.31%	61.66%

Fig. 6: Weighting results at the endpoint level for the NCS, NCS_80, NCS_eq and TVS installed in Somalia. For each damage category, the contribution analysis of the impact categories affecting the total environmental burden score is shown at the bottom of the figure.

Observing the contribution analysis results reported in **Table 5**, another major output is that the SCs are largely the most impactful components among the most relevant categories.

Table 5: Contribution analysis of the most relevant categories (>25% of the global impact on each damage category as shown in Fig. 6).

Components	Agricultural land occupation		Climate change		Particulate matter formation		Human toxicity		Metal depletion		Fossil depletion	
	NCS	TVS	NCS	TVS	NCS	TVS	NCS	TVS	NCS	TVS	NCS	TVS
Solar Collectors	15.02%	11.29%	46.00%	47.69%	57.65%	52.66%	91.33%	53.52%	59.93%	62.28%	42.03%	39.47%
Compensation Tank	1.10%	0.00%	5.81%	0.00%	3.84%	0.00%	1.73%	0.00%	3.52%	0.00%	4.92%	0.00%
Water Tanks	0.96%	1.43%	10.26%	13.44%	4.04%	5.46%	1.34%	1.34%	0.58%	0.66%	17.40%	23.12%
Heat Exchanger	1.28%	3.48%	9.01%	9.49%	10.24%	18.18%	1.84%	32.87%	15.65%	19.02%	6.89%	8.60%
Pipes	1.56%	1.24%	10.99%	7.81%	12.63%	9.17%	2.26%	1.23%	19.54%	12.16%	8.38%	6.04%
PV Panel and connections	0.00%	0.39%	0.00%	2.10%	0.00%	1.21%	0.00%	0.52%	0.00%	0.27%	0.00%	1.94%
Thermostatic Valve	0.00%	1.25%	0.00%	6.75%	0.00%	4.86%	0.00%	9.70%	0.00%	5.11%	0.00%	6.17%
Transports	0.44%	0.38%	16.77%	11.89%	11.01%	8.03%	1.34%	0.72%	0.73%	0.47%	19.31%	13.87%
Direct Land Occupation and transformation	78.37%	79.51%	0.00%	-0.02%	0.00%	-0.01%	0.03%	0.03%	0.03%	0.02%	-0.02%	-0.01%
Packaging	1.27%	1.03%	1.16%	0.85%	0.59%	0.44%	0.13%	0.07%	0.02%	0.01%	1.09%	0.80%
Recycling	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

The contribution analysis allows us to highlight that all the calculated impacts are mainly due to the manufacturing of the SCs except for the *Agricultural land occupation,* for which the surface physically occupied by the plant is the most important contributing factor. Moreover, the toxic emissions of arsenic and manganese in the life cycle of the SCs and the HEs are the main factors responsible for the impact on the *Human Toxicity* category, whereas for the *Metal and fossil depletion* category the major impacts are associated with the consumption of natural resources, especially metals (iron and copper) and fossil fuels (coal, gas and oil).

From the perspective of a possible beneficial contribution of solar pasteurization systems to the sanitary problem, a significant observation could be made by comparing, on a qualitative basis, the obtained LCA results with data regarding impact of diseases and life expectancy related with unsafe water and sanitation issues. Indeed, the WHO provides comprehensive useful data for the estimation of the sanitary conditions by countries and regions expressed in DALYs; for Somalia the reference value is estimated to be 4,465 *DALYs*/100,000 ab ([dataset] World Health Organization (WHO) (accessed on 05/04/2018), 2012). To compare with the results obtained for the *Human Health* category within the LCA analysis, this value has been normalized to the same functional unit (*DALYs*/l). To do this, it has been multiplied by the inhabitants (ab) of Somalia (considering a population of 15,181.925 ab (World Health Organization (WHO) (accessed on 05/04/2018)) and divided by water consumption data (the Food and Agriculture Organization of the United Nations (FAO) estimates a water withdrawal for municipal use of $0.15 \cdot 10^9$ m^3/year ($0.15 \cdot 10^{12}$ l/year) ([dataset] Food and Agriculture Organization (FAO) (accessed on 05/04/2018), 2003).

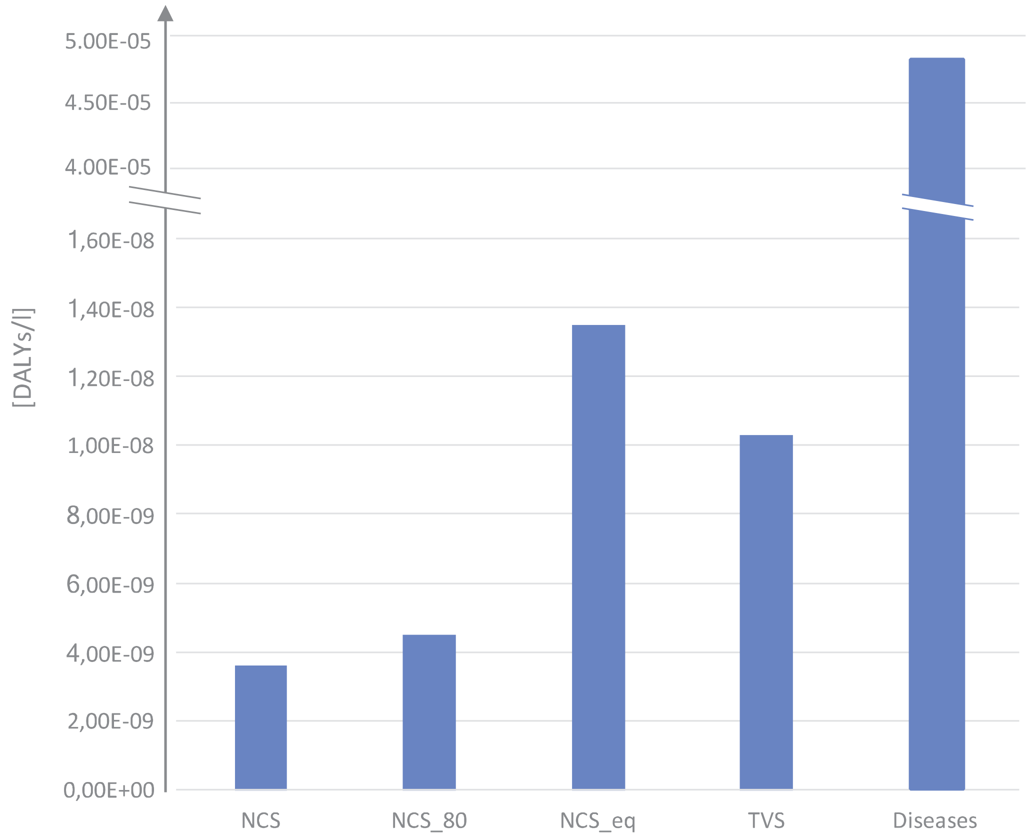
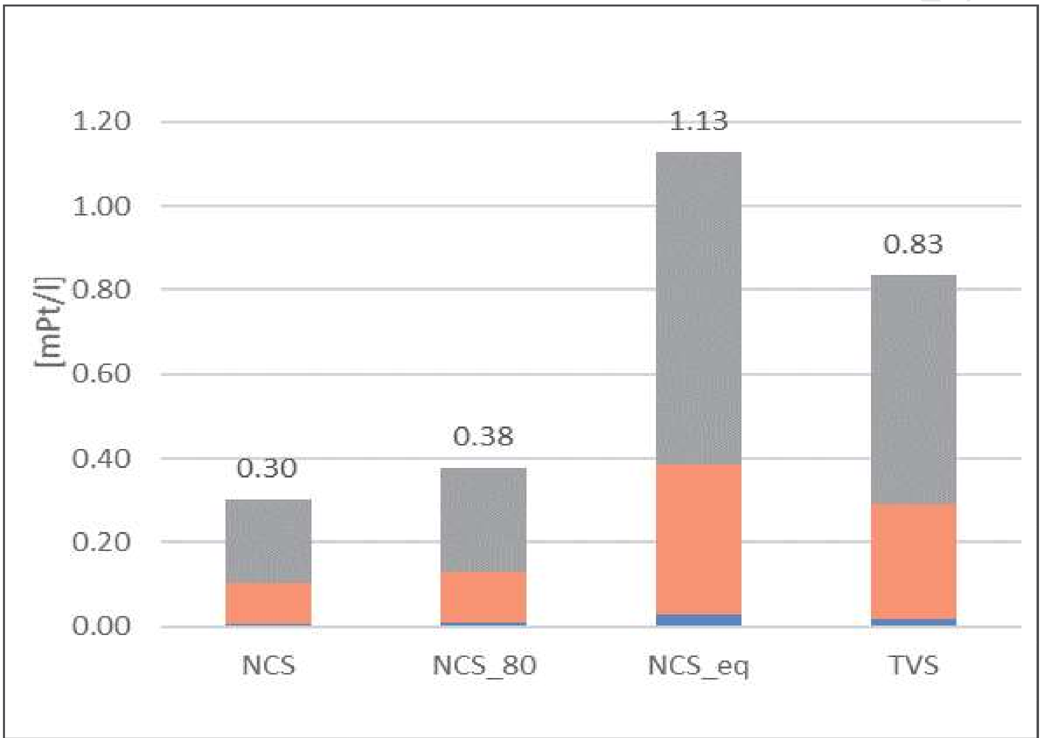


Fig. 7: Human Health damage category results at the endpoint level comparing the whole life cycle NCS and TVS impacts with that connected with unsafe water consumption impact value calculated according to the WHO and FAO estimation in Somalia.

Inspection of **Fig. 7** allows the observation that the implementation of NCS and TVS could allow a decrease in the burden of diarrhoeal diseases that is several orders of magnitude higher for the actual scenario in Somalia. Moreover, considering the above-mentioned water consumption data, a NCS would be able to satisfy the needs of about 77 people whose life expectancy is estimated to increase by 2.5 years compared to the average, that actually ranges between 54 and 57 years (World Health Organization (WHO) (accessed on 05/04/2018)). This qualitative assessment shows that in general the NCS and TVS systems could offer an effective contribution, at a limited environmental cost, to face the sanitary problems linked to unsafe water consumption.

3.2. Total environmental impact

In order to make a global evaluation of the systems based on a single score metric, weighted results are calculated referring to Somalia and are illustrated in **Fig. 8**:



	TVS	NCS
Ecosystem ■	2.5%	2.1%
Human Health ■	31.6%	32.7%
Resources ■	65.9%	65.2%

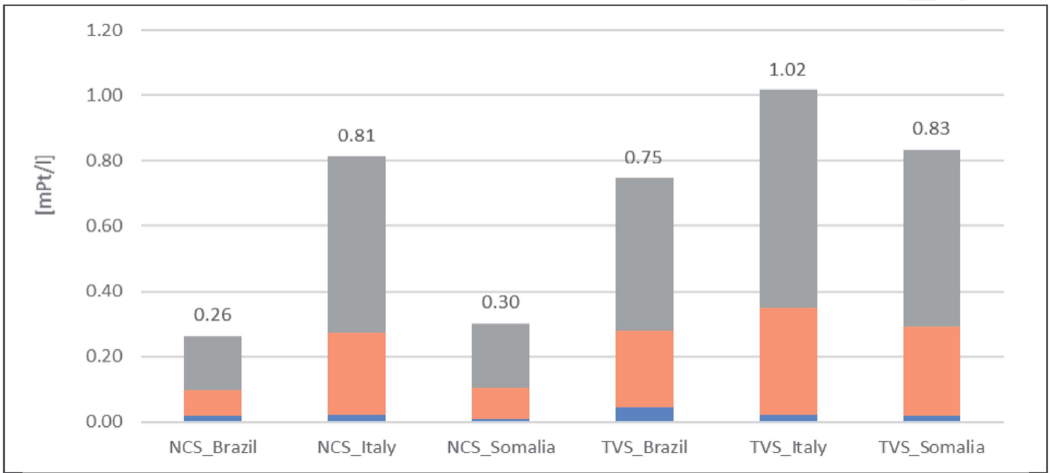
Fig. 8: Single scores of the total environmental impact (mPt/l) for the TVS and NCS (and relative operational scenarios) installed in Somalia.

Table 6: Contribution analysis of the global environmental impacts shown in Fig.8 connected to NCS and TVS components.

Components	NCS	TVS
Solar Collectors	49.32%	47.93%
Compensation Tank	4.04%	0.00%
Water Tanks	7.12%	9.19%
Heat Exchanger	10.01%	13.09%
Pipes	12.38%	8.43%
Photovoltaic Panel and connections	0.00%	1.10%
Electronics	0.00%	5.86%
Transports	8.66%	6.10%
Direct Land Occupation and transformation	7.17%	7.26%
Packaging	1.30%	1.02%
Recycling	0.00%	0.00%

The NCS is confirmed to be the most sustainable solution in ideal conditions but also in this case the conclusion strongly depends on the real productivity of the systems. The impact to the Resources category represents the main contribution to the total single score, followed by the impact on the Human Health category, while the impact to the Ecosystem category only accounts for a very low percentage. The SCs is still the most impactful component of the systems. As NCS, NCS_80 and NCS_eq scenarios only differ for the water output productivity, the damage categories percentage weights along the environmental profiles shown in **Fig. 8** do not change. In **Table 6** the contribution analysis implemented for the total environmental impact allows the investigation of the system in more detail.

Fig. 9 shows the variations of the previous results as a function of different installation sites, according to the methodological setting described in **Fig. 8**. As a matter of fact, the types of land, the installation site, distances between the installation and production site, transport modalities, water productivity and recycling rate are parameters that strongly affect the eco-profiles of the two systems.



	NCS_Brazil	NCS_Italy	NCS_Somalia	TVS_Brazil	TVS_Italy	TVS_Somalia
Ecosystem ■	7.1%	2.6%	2.5%	5.9%	2.2%	2.1%
Human Health ■	30.2%	30.8%	31.6%	31.5%	32.2%	32.7%
Resources ■	62.6%	66.6%	65.9%	62.6%	65.6%	65.2%

Fig. 9: Single scores of the total environmental impact (mPt/l) for the TVS and NCS installed in Brazil, Italy and Somalia.

Table 7: Contribution analysis of the global environmental impacts shown in Fig.9 connected to NCS and TVS components for different installation sites.

Components	NCS_Brazil	NCS_Italy	NCS_Somalia	TVS_Brazil	TVS_Italy	TVS_Somalia
Solar Collectors	39.53%	48.17%	49.32%	38.94%	46.80%	47.93%
Compensation Tank	3.16%	3.95%	4.04%	0.00%	0.00%	0.00%
Water Tanks	5.72%	6.95%	7.12%	7.08%	8.95%	9.19%

Heat Exchanger	8.55%	9.81%	10.01%	10.80%	12.79%	13.09%
Pipes	10.60%	12.13%	12.38%	7.00%	8.26%	8.43%
Photovoltaic Panel and connections	0.00%	0.00%	0.00%	0.77%	1.08%	1.10%
Electronics	0.00%	0.00%	0.00%	4.36%	5.70%	5.86%
Transports	3.89%	12.45%	8.66%	2.64%	8.75%	6.10%
Direct Land Occupation and transformation	27.96%	11.09%	7.17%	27.92%	9.93%	7.26%
Packaging	0.68%	1.25%	1.30%	0.51%	0.98%	1.02%
Recycling	-0.04%	-2.90%	0.00%	-0.02%	-1.62%	0.00%

On the basis of results shown in **Fig. 9** and details given by the contribution analysis reported in **Table 7**, some major conclusions can be drawn as follows:

- the NCSs are less impactful than the TVSs at any installation site;
- comparing these results with the productivity data from **Table 3**, it is evident that in sites with higher productivity, such as Brazil, the environmental impact is lower for both NCS and TVS; on the other hand, when the productivities are more similar, like for the Italian installation site, it can be noted that differences between the eco-profiles of NCS and TVS are quite smaller; thus confirming that the productivity of any technological solution is crucial for the environmental assessment.

- an environmental benefit (i.e. a positive impact) from recycling option is appreciable only in Italy, even if it can counter-balance the lower productivity of the systems only in a somewhat limited way;
- the contribution of direct land occupation and transformation is always quite low, except for Brazil where the calculation methods associate a high impact factor to the transformation of forest, considered as natural land.
- the percentage impact of transportations is always low and ranges between 2.64% and 12.45% of the total, that is a quite limited contribution considering the variability of distances and modes of transports assumed in this study. The main reason is that the impact of transports also depends on the weight of the transported goods, that in this case is represented by systems designed to be not massive. Furthermore, we can observe that, despite the shorter distances, transportation in Italy gives a higher contribution with respect to the other countries because transport by road is the most impactful mode according to the impact weighting factors employed by the calculation method.
- SCs represent the most impactful components in every country.

To perform a qualitative assessment aiming at understanding the advantages or limitations connected with the implementation of solar pasteurization systems and, consequently, to evaluate our analytic model, we compare the cradle-to-gate eco-profiles of NCS and TVS virtually functioning in Somalia, Brazil and Italy with the impact single score values of unsafe water related diseases in the different geographical contexts.

The environmental impact of diseases connected with unsafe water consumption in Brazil and Somalia has been estimated using the same approach described for the Somalian case (paragraph 3.1) and a single score has been obtained considering the burden to the *Human Health* damage category as the only relevant impact, neglecting the effect of the diseases on the *Ecosystems* and *Resources* damage categories (**Fig. 10**).

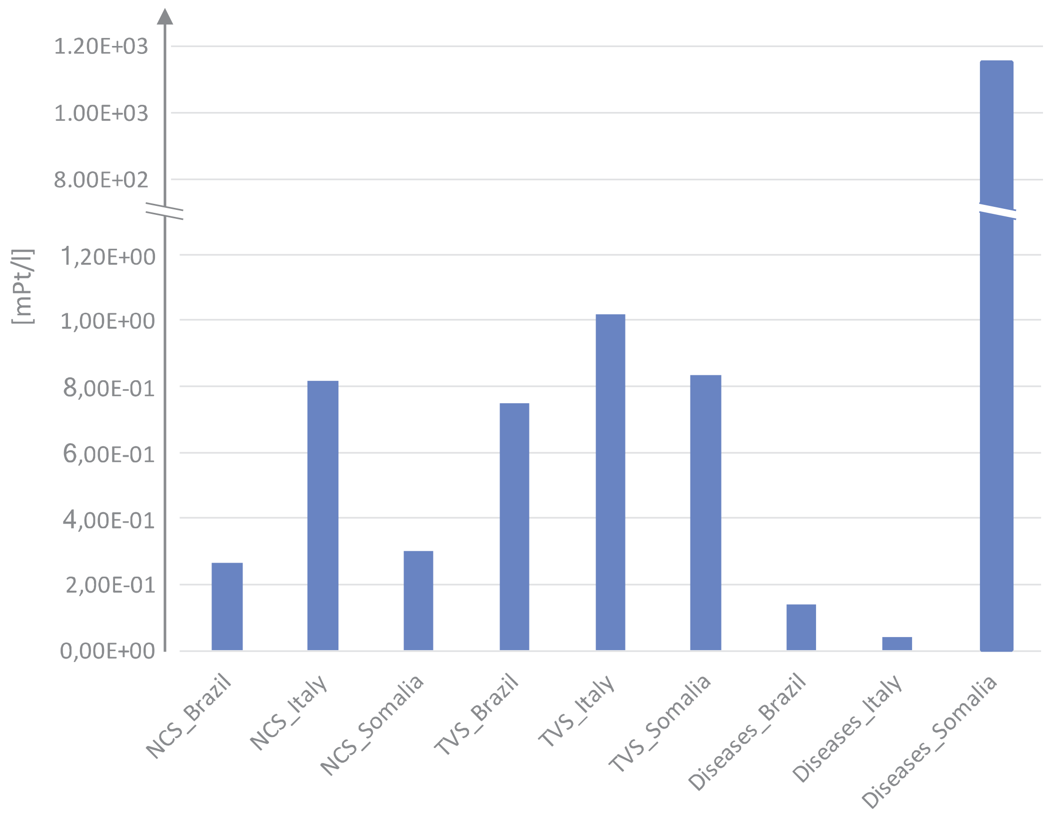


Fig. 10: Single score values of the total environmental impact comparing the whole life cycle of NCS and TVS burdens with that connected with unsafe water consumption impact value calculated according to the WHO and FAO estimation in Brazil, Italy and Somalia.

Fig. 10 is useful to understand the order of magnitude and the diffusion of the sanitary problem in the analysed situations giving an idea of how and to which extent a NCS or a TVS could be effective in a particular geographical context. In Brazil and in Italy, the impact of the unsafe water consumption is lower than the impact of Pasteurization systems, so a Pasteurization system would be convenient only in few specific emergency situations. Indeed. these results are estimated using data on a national scale. Different conclusions would be reached if data from more specific regional case studies (not available) would have been used. For instance, some of Brazilian regions still have sanitary problems connected to water consumption (Marques et al., 2013) thus the use of solar pasteurization systems could be very advantageous for these sites. In Somalia, however, since the burden of sanitary problems related to unsafe water consumption is significantly higher, the installation of solar pasteurization systems would be extremely beneficial.

From a general methodological point of view, the outcomes of such assessment allowed us to prove the robustness of our product system model finding out that it responses rather well to the water's sanitary conditions context. In the perspective of providing an assessment procedure to support the political decision making, this model would allow to perform ex-ante qualitative assessment to investigate the environmental advantages and costs of several technological solutions and to recommend the best option for a given geographical context.

3.3. Energy and exergo-environmental analysis

In this section a comparison between Solar Pasteurization systems and other technologies for which the SCs are hypothetically replaced with fossil fuels combustion systems is presented. This estimation is made replacing the SCs with a boiler in the model system and considering that boilers useful life is longer and that they could be re-used after 15 years.

Based on the previous results according to which the most environmentally sustainable solution is the NCS, the following analysis is focused on this system installed in Somalia, as it is the country experiencing the highest need for water sanitation intervention among those considered in this study. The amount of heat required by a NCS in Somalia is estimated by the mathematical model described by Dainelli et al. (2017) and Manfrida et al. (2017).

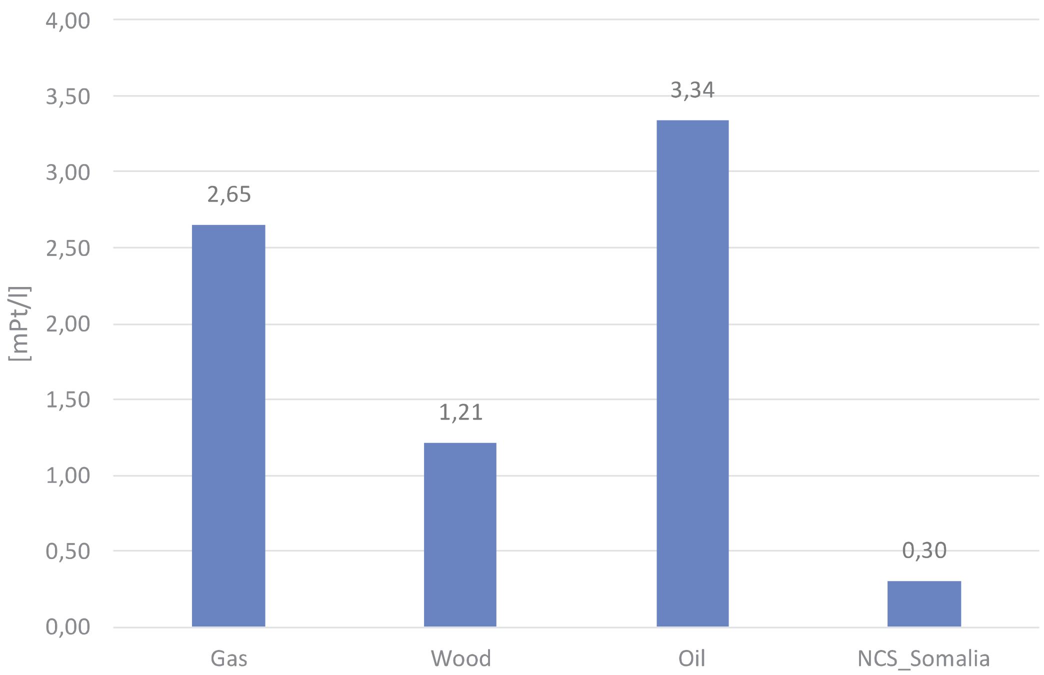


Fig. 11: Single score values of the total environmental impact calculated for different pasteurization systems. The comparison is performed based on an equivalent heat amount provided by solar energy, biomass and fossil fuels.

Inspection of **Fig. 11** reveals that, as expected, the use of solar energy is responsible for a lower environmental impact than the other analysed options, even if the SCs result to be a very impactful components, as shown in the contribution analysis in **Table** 7. Indeed, if boilers burning oil, gas or wood (some of the fuels mainly used in rural areas of Somalia (UNEP, 2015)) were used, the generated environmental impact would be at least four times higher.

The exergo-environmental analysis can provide a further insight: the environmental impact associated to the exergy content of treated water is equal to zero because solar energy is used and only the results calculated through the LCA study give a relevant contribution to the analysis. On the other hand, the exergy destructions inside the components occur anyway; they are due to the thermodynamic irreversibility such as the friction and the mixing of different flows of water inside the pipes and in the CT and the finite temperature heat exchange inside the SCs.

The exergo-environmental analysis results are averaged over each year and collected in **Table 8** showing that the exergy destructions due to the irreversibility of water's warming inside the SCs determine a sizeable environmental impact (B_D) compared to the one related to the SCs' construction, maintenance and disposal (Y). The reason is that a source of energy at very high temperature (Sun) is used to heat water up to a temperature lower that 100 °C. This observation is coherent with the results obtained by Dainelli et al. (2017) and Manfrida et al. (2017) showing that the exergy losses and destructions of the SCs are much higher than those of other components of the plant. So, in the SC case, the exergo-environmental factor f_d (which represents the contribution of Y to B_{TOT}), accounts for a very small percentage value. Despite the damage of exergy destructions, the relative environmental impact difference (r_d) across the SCs is negative; this happens because the direct input of renewable solar energy, which improves the exergy content of the fluid, takes place at zero environmental cost.

The second most impactful component in terms of total environmental impact (B_{TOT}) is the CT; the main reason is the exergy destructions burden (B_D) due to the time-variable exergy content of stored water and to the mixing with the inlet stream. The effect of this irreversibility is an increase of the specific environmental cost (r_d) of the outlet flow from the CT. For such reason the cradle to grave LCA result (Y) accounts for a very low percentage (f_d) of the total damage.

The third largest contribution in absolute terms (B_{TOT}) is given by the HE; among the other components, only the HE determines a very relevant increase of the environmental cost of exergy (r_d). In this case the contribution of exergy destructions (B_D) is high, as demonstrated by the low exergo-environmental factor (f_d). However the performance cannot be improved by simply using a larger heat exchange surface because the ratio of recirculating and supply flows is limited by the natural circulation mechanism and the system should be operative – after the warm-up – at temperatures between 85 and 100°C (Dainelli et al., 2017; Manfrida et al., 2017).

The total environmental impact (B_{TOT}) of pipes is quite low and a significant contribution is represented by the exergy destructions burden (B_D) due to the frictions and the mixing of the supply and the recirculating flows.

The WTs are at the borders of the system, so no exergy balance is possible for them and thus their exergy destructions have been neglected (Dainelli et al., 2017; Manfrida et al., 2017).

Table 8: Exergo-environmental analysis results of the NCS system concerning the impact of the irreversibility (B_D), the cradle to grave LCA result (Y), the global environmental impact (B_{TOT}), the exergo-environmental factor (f_d) and the relative environmental impact difference (r_d).

Components	B_D	Y	B_{TOT}	f_d	r_d
	[mPt/ l]	[mPt/ l]	[mPt/ l]	[%]	[%]
Solar Collectors	19.69	0.16	19.85	0.81%	-13.68%
Compensation Tank	1.03	0.02	1.05	1.90%	6.01%
Heat Exchanger	0.70	0.04	0.74	5.41%	124.50%
Pipes	0.20	0.05	0.25	20.00%	18.71%
Water Tanks	0.00	0.03	0.03	100.00%	0.00%

3.4. Sensitivity analysis

The sensitivity analysis is a significant tool for studying the robustness of LCA outputs and their sensitivity to uncertainty factors, thus enhancing the interpretation of results. (Saltelli, 2002). In previous sections, to investigate the dependency of the model system on operational and geographical factors, the variation of the productivity and of the installation sites have already been considered. Nevertheless, considering the significant impact of the SCs on the environmental impact assessment, a sensibility analysis of the SCs' dimension will be performed here.

The installation site of the NCS is set in Somalia; the surface occupied by the SC is supposed to vary in the range ±15%. As a preliminary speculation, the productivity of the system is set to be constant and so the environmental impact increases linearly with the SC's area in a range of ±10% (**Fig. 12**).

Applying the perturbation of the SC's area to the mathematical model described by Dainelli et al., (2017) and Manfrida et al., (2017), the corresponding variation of productivity can be evaluated. In this case the results show a contrary non-linear trend because environmental impacts decrease sensibly with an increasing of the SC's area and vice versa; variations are assessed between -20% and +35%.

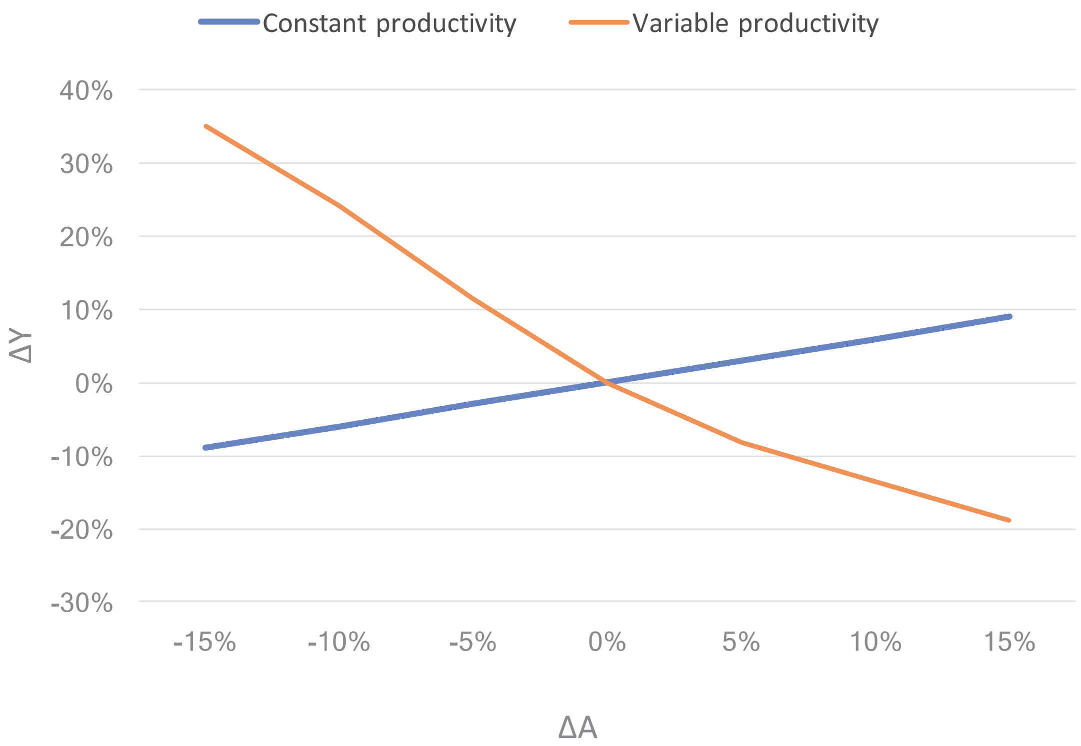


Fig. 12: Sensitivity analysis of the environmental impact (ΔY) respect to the surface of the SC (ΔA) with constant and variable productivity.

4. Conclusions

Many regions of the world are affected by serious sanitary conditions due to the consumption of contaminated water. The role of this primary element as a vector of several kinds of diseases, especially diarrhoeal, has been investigated from a humanitarian and sanitary point of view, but a comprehensive approach to this problem cannot overlook also the strictly connected environmental and energetic issues in order to propose an integrated solution. In this context, the choice of the best technical solution to purify water from pathogens should be based on criteria that take into consideration these aspects to individuate simple, reliable and sustainable technologies. This is particularly relevant to address the objectives of SDGs of the Agenda adopted by the General Assembly of the United Nations, in particular those of Goal 6 which focuses on "Ensure availability and sustainable management of water and sanitation for all". In this study, an LCA and an exergo-environmental analysis have been integrated to propose a methodological framework useful for environmental sustainability assessment to support the political decision making for the choice of the best technically and environmentally solution for a specific geographical context.

The assessment of Solar Pasteurization Systems performances has been carried out in different conditions. First, these plants are supposed to be installed in Somalia where sanitary problems connected with unsafe water consumption are very critical. Indeed, we can conclude that a NCS would be more sustainable than a TVS thanks to its higher productivity: under ideal conditions the total environmental impact of the analysed NCS is calculated to be 0.3 mPt/l, versus 0.83 mPt/l of the TVS. A significative output of the analysis is represented by the eco-profiles calculated for both plants that show a substantial total environmental impact reduction compared to the actual sanitary scenario. It is estimated that the human life expectancy could be at least two years longer thanks to the application of a disinfection device. Different installation sites (Somalia, Brazil and Italy) have been considered and in all cases the NCS results more sustainable than the TVS: in Brazil very similar results to Somalia are evaluated and they are respectively 0.26 mPt/l for the NCS and 0.75 mPt for the TVS; in Italy the impact is higher because of a lower water productivity and thus the difference between the two systems eco-profiles decreases (0.81 mPt/l for the NCS and 1.02 mPt/l for TVS). The results show that the best installation site, from an environmental point of view, is in Brazil but considering the burden related to the consumption of unsafe water, Somalia represents the most critical situation and it would be very advantageous to employ these systems on a large scale; in Brazil and in Italy the installation could be beneficial only in specific situations because, in general, the impact of unsafe water related diseases is lower than the whole systems eco-profiles. From the energetic point of view, the saving of fossil resources due to the use of solar energy represents an environmental benefit respect to the installation of boilers burning gas, wood or oil to produce an equivalent amount of heat because their environmental impacts are higher (respectively

2.65 mPt/l, 1.21 mPt/l, 3.32 mPt/l). The exergo-environmental analysis shows that no direct environmental damages occur during the operative phase but considering the contribution of exergy destructions, the SCs resulted to be the most impactful component. This conclusion is confirmed also by the LCA that estimates their contribution to the global environmental impact in the range 39-49%. A sensitivity analysis performed for the NCS shows that the surface of the collector is a very crucial parameter because variations from -15% to +15% of the surface determine an increasing of the impact that varies between -10% to +10%, but the model is also very dependent on the productivity because the increasing of treated water due to a higher thermal exchange surface would balance it and make the environmental impact sensibly lower; the variations are assessed between +40% and -20%.

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Notes

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Highlights

- LCA and exergo-environmental analysis are used to evaluate environmental impacts;
- NCS results more sustainable (0.30 mPt/l) than TVS (0.83 mPt/l) in Somalia;
- The most influencing parameter for the result is the systems' water productivity;
- The SCs represent the most impactful components in both systems (about 45%);
- The SCs exergy destructions are more impactful than their LCA burdens.