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Research paper

Life Cycle Assessment of heat exchange systems for Concentrated Solar Power plants

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ABSTRACT

Concentrated Solar Plants (CSP) are among the most promising technologies in the field of renewable energies exploitation. In the present paper, a novel Modular Air Cooled Condenser (MACC), developed under the EU funded MACCSol research project, is compared with two standard condensers – a Water Cooled Condenser (WCC) and an Air Cooled (ACC) Condenser – in a reference Concentrated Solar Power (CSP) plant, at the aim of evaluating the different cooling options in terms ofenvironmental impacts. The LCA (Life Cycle Assessment) methodology is being used and the life cycle impacts are evaluated through different methods: IPCC 2007, Ecoindicator 99 and Ecological Scarcity 2006, which takes into account freshwater consumption that is one of the main issue of CSP plants.

Results show that the impact of the MACC is quite lower than the ACC one, according to all the evaluation methods. With the Ecological Scarcity 2006 approach, since the condensers operate in medium water stress conditions, the WCC is the cooling option with the highest impact and the MACC came out as the best solution. Therefore, the MACC condenser represents a valid alternative to the conventional cooling solutions in regions suitable for CSP plants, with environmental benefits more evident with the increase of the Direct Normal Irradiance (DNI). The planning of transport activity emerged as a key issue to further optimize the life cycle impacts of the MACC.

Keywords: Concentrated Solar Power; Condensers; Air cooled; Water cooled; LCA; Water consumption.

1. Introduction

The share of renewable energies in the global energy mix is regularly increasing (Moncada Lo Giudice et al., 2013) and in 2011 it reached 13% of the world primary energy demand (IEA, 2013). Among all renewables, concentrated solar power (CSP) is considered one of the most promising technologies and it is expected to grow fast globally, with a energy potential production estimated to be 2.5 % of EU energy demand by 2020 (European Commission 2008). CSP plants operate on the basis of a Rankine cycle and the condensation of the steam exiting the turbine is obtained by means of water-cooled condensers (WCCs) or air-cooled condensers (ACCs). The former are characterized by a high cooling efficiency, but require large water quantities to operate. The latter, instead, allow to reduce the water consumption up to 90 %, at the expense of a sensible reduction of CSP plant global efficiency. The higher fan power consumption, related to the difficulty of ACCs to respond to daily variations of ambient temperature, and also to their inability to maintain optimum values of pressure and temperature at the condenser, in fact, may generate a reduction of CSP plant net power output up to 25 % on warm days (Poullikkas et al., 2011).

The MACCSol research project, co-funded under the EU's 7[th] Framework Program, addressed the development of an innovative modular air-cooled condenser (MACC) able to reduce the typical inefficiencies of conventional ACCs, thus aiming at supporting the deployment of CSP

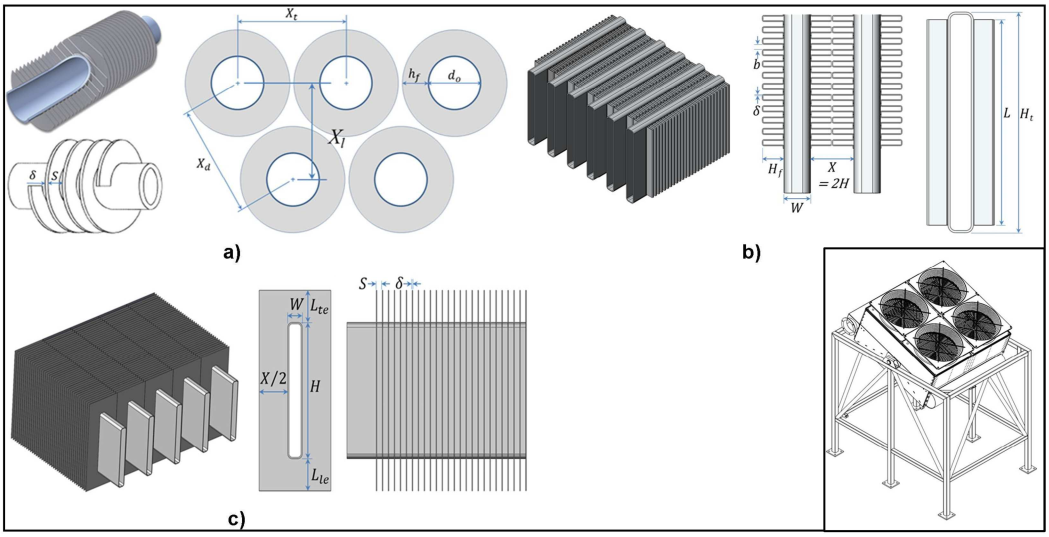

Fig. 1 - MACC module layout and tube bundle geometries. a) Circular finned; b) Continuous finned; c) Plate finned

plantsin desert areas. Among all the different prototypes designed during the course of the project, one consists of 2·2 m^2 modules that use small diameter fans (1 m) and which could be equipped with three different kinds of tube bundle geometries: circular finned, plate finned, and continuous finned.

This paper presents the comparison of a specific configuration of the MACC condenser (300 modules, circular finned tube bundle) with two conventional condensers, operating in a reference 20-MW CSP plant, carried out through a life cycle assessment (LCA) approach. LCA is broadly used for the evaluation of the environmental impact of renewable energies and, in particular, of solar technologies (Jungbluth et al., 2005; Suwanit and Gheewala, 2011; Davidsson et al., 2012; Traverso et al., 2012; Bayer et al., 2013; Garrett et al., 2013; Koroneos and Stylos, 2014), but it is not so commonly applied to single components of renewable energy power plants.

The research carried out was specifically aimed at this kind of analysis, i.e. at comparing different steam condensers for CSP plants, taking into account their main environmental issue: freshwater consumption.

2. Description of the innovative air-cooled system

A general overview of conventional condensers is provided in (Asdrubali et al., 2013).

The MACC configuration here investigated consists of square modules with a side length of 2 m, which use 1-m diameter fans to blow air – both in forced draft or induced mode – across the tube bundle where the steam flows.

The tube bundle of the module could be arranged with different layouts and, in particular, it could be equipped with circular finned, plate finned, or continuous finned tubes (Fig. 1).

An optimization analysis (Asdrubali et al. 2013) demonstrated that a circular finned configuration represents the best solution in terms of thermodynamic, economic and environmental performance.

The module uses variable speed fans that work on the basis of a key parameter: the water temperature at the end of the expansion, which is ambient temperature-dependent. Thus, an increase or a decrease of the temperature will be offset, respectively, by an increase or a decrease of the fans rotational speed, at the aim of guaranteeing optimum operating conditions, with the consequent optimization of power consumption.

These innovative aspects reduce parasitic power losses that typically affects current ACC designs and allow to obtain a significant CSP plant power output increase (Moore and Grimes 2011; Walsh and Griffin 2011; O'Donovan et al. 2014; O'Donovan and Grimes 2014).

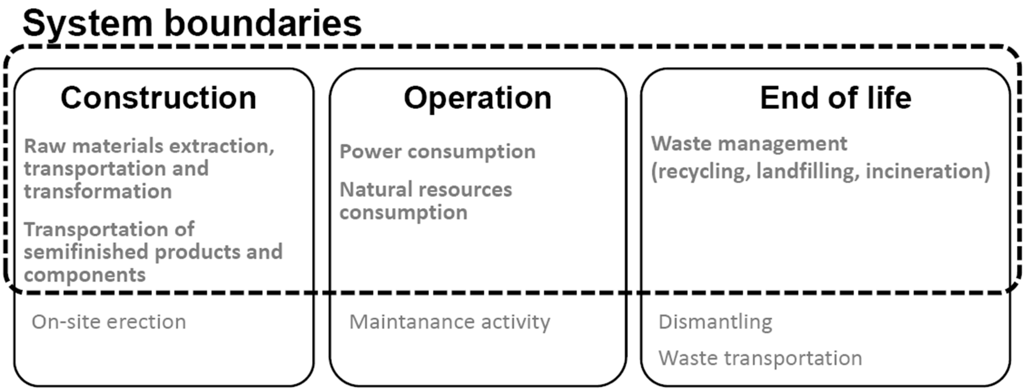

Fig. 2 - System boundaries adopted for the LCA

3. Methodology

3.1. LCA study

The goal of the LCA is the comparison of the MACC prototype with a conventional WCC and a conventional ACC, all operating in a central tower (CT) CSP plant. The production/construction of materials/components, the transports (both to manufacturing company and to CSP site, implementing two different scenarios), the operation, and the handling of materials at the end of life of the condensers are included in the system boundaries. Following the usual system boundaries in LCA of CSP plants CSP (Lechón et al., 2008; Burkhardt et al., 2011; Desideri et al., 2013; Corona et al., 2014) it was decided to exclude some processes, such as condenser erection, maintenance, and dismantling activities. Data concerning erection and dismantling activities are closely related to the technology adopted and to the characteristics of the construction site; since specific data were lacking, these processes were omitted in order to limit the uncertainty affecting the results (Fig. 2). On the other hand, the maintenance activities on the condensers could be considered negligible during the 15 years life cycle of the CSP plant. During this period, in fact, a marginal routine maintenance for each condenser (e.g., reintegration or replacement of the lubricating oil in the gearbox) is expected, which does not significantly affects the life cycle impacts.

The functional unit chosen, i.e. the reference unit to which inputs and outputs are related, is 1 kWh of electricity produced by the plant (excluding self-consumed power) and delivered into grid. The life cycle impacts were then referred to 1 year of plant operation, which is the normalization period chosen for the comparison.

3.2. Impact assessment

The LCA study was implemented in SimaPro 7.3 (PRé Consultants) and, among all the assessment methods, the IPCC 2007 method – which characterize the different gaseous emissions according to their global warming potential (time horizon 100 years) and aggregates them in a single impact indicator (CO_2 equivalent emissions) – and the Ecoindicator 99 method – which considers a total of 11 impact categories regarding the damage to human health, ecosystem quality, and resources – were used.

Furthermore, in order to evaluate the severity of the local impact associated to freshwater consumption in specific water stress conditions, the assessment was also carried out through the Ecological Scarcity 2006 method. Freshwater consumption represents one of the main environmental issues of power generation (Pfister et al., 2011) and even more of CSP plants. Its shortness can be evaluated through the scarcity ratio (SR), which represents the ratio between water withdrawal and water availability, and the water stress can be classified as follows (Alcamo et al., 2000; Vörösmarty et al., 2000; OECD, 2004; Oki and Kanae, 2006):

- Low, with SR < 10 %;
- Moderate, with 10 % ≤ SR > 20 %;
- Medium, with 20 % ≤ SR > 40 %;
- High, with SR ≥ 40 %.

In the Ecological Scarcity 2006 method two

Tab. 1 - WCC main design characteristics

WCC data		
Tower type	Crossflow, Fill Film	
Total number of cells in tower	4	
Number of rows	1	
Length of cell	6.4	m
Width of cell	5.7	M
Basin area	193.6	m^2
Water basin temperature	26.45	°C
Water temperature range	9.87	°C
Cold water approach to inlet wet bulb	7	°C
Heat water approach to exit wet bulb	5	°C
Fan diameter	4.3	m
Design volume flow per fan	135.9	m^3/s
Fan electricity consumption	37.69	kW
Cooling tower total heat rejection	30,399	kW

additional water stress conditions are defined (very high stress, 60 % ≤ SR > 100 %, and extreme stress, SR ≥100 %), and the environmental impact of each category considered is weighted by applying an "eco-factor" (FOEN 2009) that depends on SR (Eqs. (1)–(3)[1]).

$$\text{Eco} - \text{factor} = K \cdot \frac{1 \cdot EP}{F_n} \cdot W \cdot c \qquad (1)$$

where:
K = characterization factor of a pollutant or of a resource;
F_n = normalization flow: current annual flow in Switzerland;
c = constant (=10^{12}) to obtain readily numerical quantities;
EP = Eco-points: unit of environmental impact assessed;
W = weighting factor:

$$W = \left(\frac{F}{F_k}\right)^2 = \left(\frac{\text{current annual flow in the reference area}}{\text{critical annual flow in the reference area}}\right)^2 \qquad (2)$$

$$W = \left(\frac{\text{Water Consumption}}{\text{Available Resource} \cdot 20\%}\right)^2 = SR^2 \cdot \left(\frac{1}{20\%}\right)^2 \qquad (3)$$

3.3. CSP plant description and condensers design

The reference plant for the comparative analysis is the Gemasolar power plant, a 20-MWCT CSP plant located in the south of Spain, which is equipped with a storage system and uses molten salts both as heat transfer fluid and storage medium. The solar field consists of 2,650 heliostats (global footprint area of about 185 ha) and the storage capacity is 15 h. The mean annual electricity production is 110,000 MWh. The CSP plant is equipped with a WCC characterized by the main design data summarized in Table 1. The ACC and the MACC were specifically designed for the comparison, assuming a maximum backpressure accepted by the steam turbine of 300 mbar and, respectively, a minimum backpressure in operation of 60 mbar and 30 mbar (Tables 2 and 3) (MACCSol, 2013).

[1] A moderate to medium pressure on water resources is considered as tolerable and, therefore, the 20% of the available resources represent the critical value of freshwater consumption.

Tab. 2 - ACC main design characteristics

ACC data		
Condenser tube geometry	Rectangular	
Fin-tube type	Solid fins	
Tube arrangement	In line	
Total number of cells	9	
Number of bays	3	
Number of cells per bay	3	
Overall Length	24.69	m
Overall Width	24.69	m
Plot area	609.6	m^2
Fan diameter	6.39	m
Design volume flow per fan	258.7	m^3/s
Fan electricity consumption	43.16	kW
Overall heat transfer coefficient	23.51	W/m^2 K
Heat transfer rate to gas	3.084	kW
Heat transfer rate from water	3.084	kW
Overall heat transfer coefficient (UA)	326.4	kW/K

Tab. 3 - MACC main design characteristics

MACC data		
Number of modules	300	
Number of fans per module	4	
Fan speed	0 - 1000	rpm
Fan diameter	0.91	m
Tube geometry	Circular	
Tube material	Stainless steel	
Fin Material	Aluminium	
Tube length	2	m
Number of rows	6	
Longitudinal tube pitch	55.86	mm
Transverse pitch (X_t)	64.5	mm
Tube outer diameter (d_o)	31.75	mm
Tube wall thickness	2.9	mm
Fin thickness (δ)	0.40	mm
Fin spacing (S)	2.5	mm
Fin height (h_f)	15.9	mm

3.4. Life Cycle Inventory data

The inventory data regarding the construction materials of the WCC and the MACC were directly gathered from the design documents for a single WCC cell and a single MACC module. The inventory of each condenser was therefore calculated multiplying the data by the total number of elements:

$$I_i = n \cdot I_{i,d} \quad (4)$$

where:

I_i = inventory data regarding the i-th component

n = number of WCC cells/MACC modules constituting the condenser

$I_{i,d}$= inventory data regarding the i-th component collected from the design documents

The design documents available for the ACC, instead, were those of the condensers installed in two existing power plants, both with a capacity of around 400 MW. Therefore, an adaption of the inventory data to the characteristics of the condenser as designed for the comparative analysis was done (Table 2) adopting a scaling factor, calculated as the ratio between the dimensional characteristics of analogous components:

$$I_i = \frac{D_i}{D_{i,d}} \cdot n \cdot I_{i,d} \quad (5)$$

where:

I_i = inventory data regarding the i-th component;

n = number of A-frames constituting the condenser;

$I_{i.d}$ = inventory data regarding the i-th component collected from the design documents

D_i = dimensional characteristic of the i-th component;

$D_{i,d}$= dimensional characteristic of the i-th component from the design documents.

The transports from the semi-finished manufacturing companies to the component producer companies were modeled considering a mean distance equal to 30 km, while the distance from the latter to the CSP site was evaluated through specific GIS software. A first transportation scenario was implemented assuming the use of truck and container ship as means of transport, while in a second scenario the use of truck and aircraft was considered.

The power consumption in the operation phase of the condensers, due to fans and auxiliary components, was estimated through a dedicated modeling (MACCSol 2014) and used to calculate the annual net energy output of the plant. The cooling water consumption was evaluated on the basis of the available design documents.

The end of life scenario was supposed considering statistic data (European Commission 2014) and it splits the waste management activities as shown in Table 4.

Inventory were implemented in SimaPro using the Ecoinvent 2.2 datasets and creating specific processes if necessary (e.g., for the power consumptions in the operation phase, since the electricity consumed is produced by the CSP plant, a process was created taking into account the life cycle of the CSP plant itself, excluding the condenser in order to avoid double counting).

Tab. 4 - End of life scenario

Material	Recycle (%)	Landfill (%)	Incineration (%)
Steel	93	7	-
Aluminum	80	15	5
Copper	90	-	10
Plastics	47	25	28
Others	-	100	-

4. Results

Life cycle impacts presented in the following figures are those referred to transportation scenario 1; scenario 2 shows a similar trend, with a slight increase in the impact values. Looking at CO_2 equivalent emissions (Fig. 3), the dry-cooled condensers are characterized by an overall impact significantly higher than the one of the WCC. This is basically due to the nature of the construction materials used in the ACC and in the MACC, which are characterized by a higher impact per unit of mass and by a higher specific weight that also generates a considerable increase of the impact associated with the transports. It is worth noting that the impacts of the construction and operation of the MACC are considerably lower than the ones of the ACC (respectively, −21.5 and −41 %), and that this fact generates an overall impact of the MACC appreciably lower than the one of the ACC (about 21 % less), despite the minor impact reduction related to the recycling at the end of life (about 28 % less). Moreover, it is noteworthy that, differently from the dry-cooled

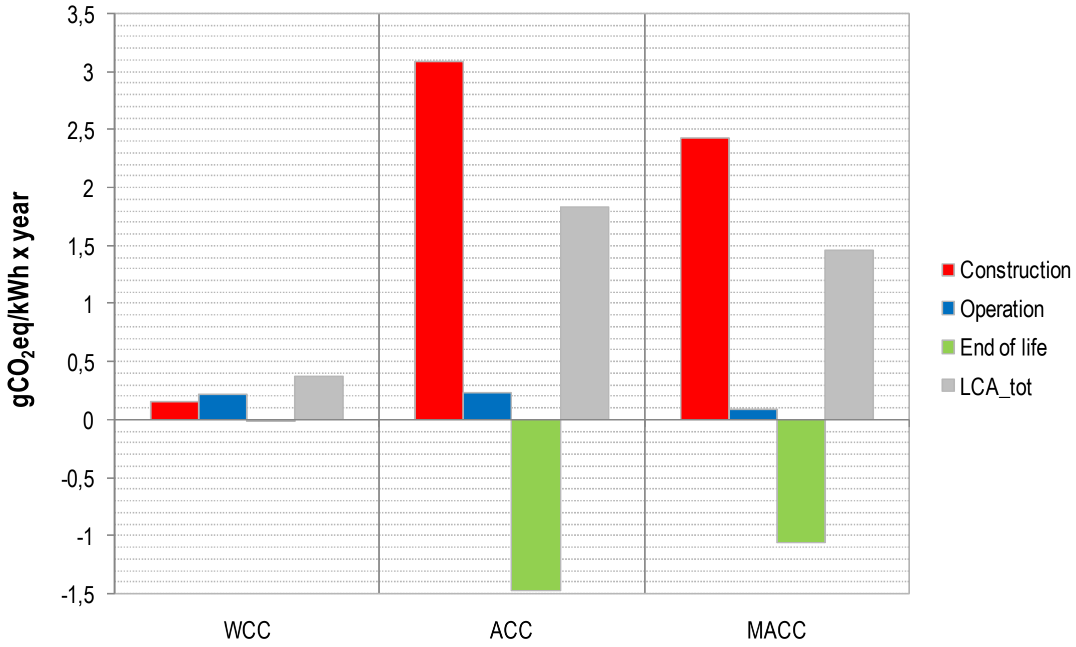

Fig. 3 - Overall impact of the condensers (IPCC 2007 method, GWP 100 years)

condensers, the impact of WCC operation is higher than the impact of its construction, and the impact reduction due to WCC materials recycling is negligible.

The Ecoindicator 99 method results are characterized by a similar global trend and show a more appreciable difference between the impact of the MACC and the impact of the ACC, thus confirming the environmental advantages related to the use of the innovative dry-cooled system, compared to conventional ACCs (Fig. 4). The overall impact reduction is -27.5 %, with the impact of the construction 13.2 % less, the impact of the operation 41 % less, and a very similar impact reduction due to the recycling at the end of life. Otherwise, all the life cycle phases of the WCC contribute positively to its overall impact.

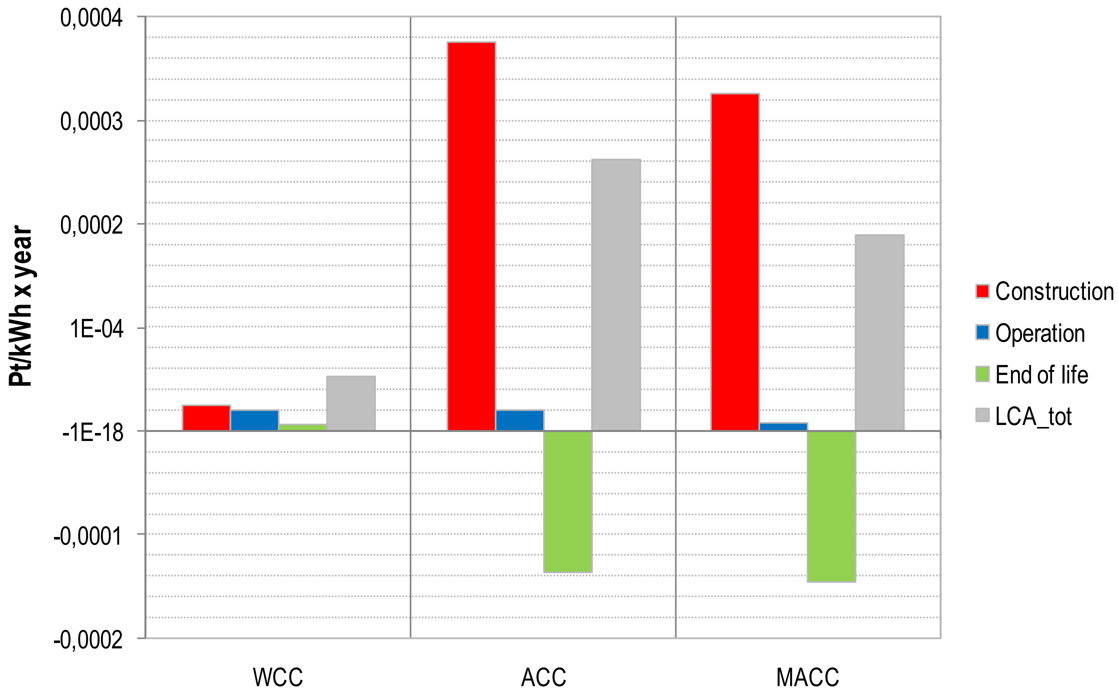

Fig. 4 - Overall impact of the condensers (Ecoindicator 99/H method)

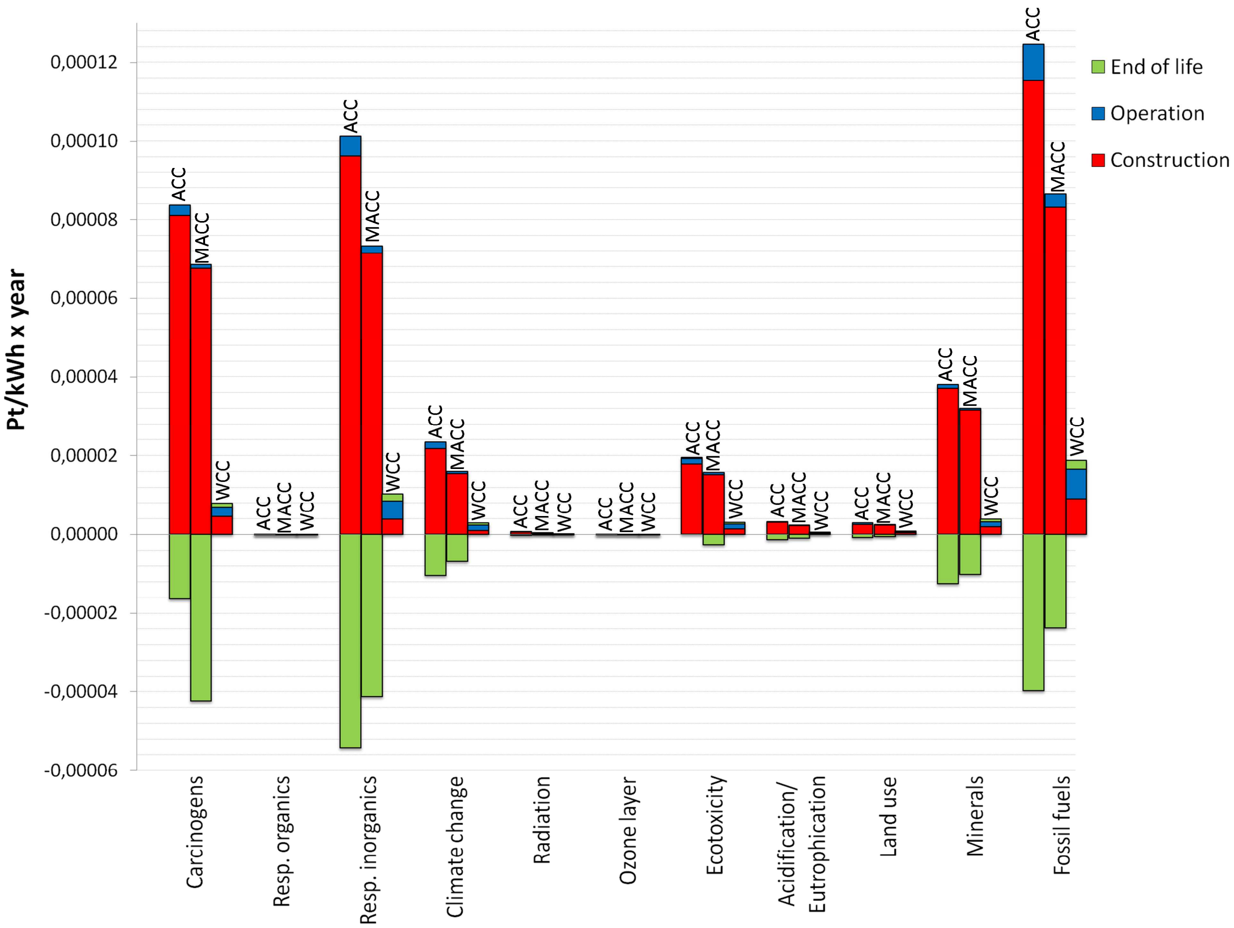

Fig. 5 - Breakdown by category of the overall life cycle impact (Ecoindicator 99/H method)

The breakdown of life cycle impacts by category (Fig. 5) shows that the main contributing categories are "carcinogens", "respiratory inorganics" and "fossil fuels", which together give a contribution equal to 76.8 % of the WCC overall impact, 76 % of the ACC overall impact, and 71.6 % of the MACC overall impact. The remaining part of the overall impact of each condenser is mainly due to the categories "minerals", "ecotoxicity", and "climate change", which jointly contribute for the 20.4 % for the WCC, 22.2 % for the ACC, and 26.1 % for the MACC. The other categories ("acidification/eutrophication", "land use", "ozone layer", "radiation", "respiratory organics") give together a contribution included in the range of 1.8–2.9 %.

Life cycle impacts evaluated through the Ecological Scarcity 2006 method (Fig. 6) show the MACC condenser as the best cooling option, with an overall impact 33 % less compared to the conventional ACC and 50.5 % less compared to the WCC. "Emission into air" is the category that mainly contributes to the impact of the dry-cooled condensers, accounting for more than a half of the overall impact (55.3 % for the MACC and 63.9 % for the ACC) and for the most of the construction and operation impacts (about 70 % for both the condensers). The contribution of "emission into air" for the WCC, instead, is equal to 8.7 % of the overall impact, 76.5 % of the construction impact and 5.5 % of the operation impact (Fig. 7).

"Natural resources" is the category that takes into account the impact related to freshwater consumption and it contributes to the impact of the WCC with a share equal to 84.2 %. On the other hand, its contribution to the impact of the ACC and the MACC is about 1 %. This fact is the consequence of the WCC operation, i.e., of the high water consumption in the "medium" stress conditions (eco-factor equal to 880, Table 5) that characterize Spain and also of the treatment of complete softening to which it is subjected before its utilization.

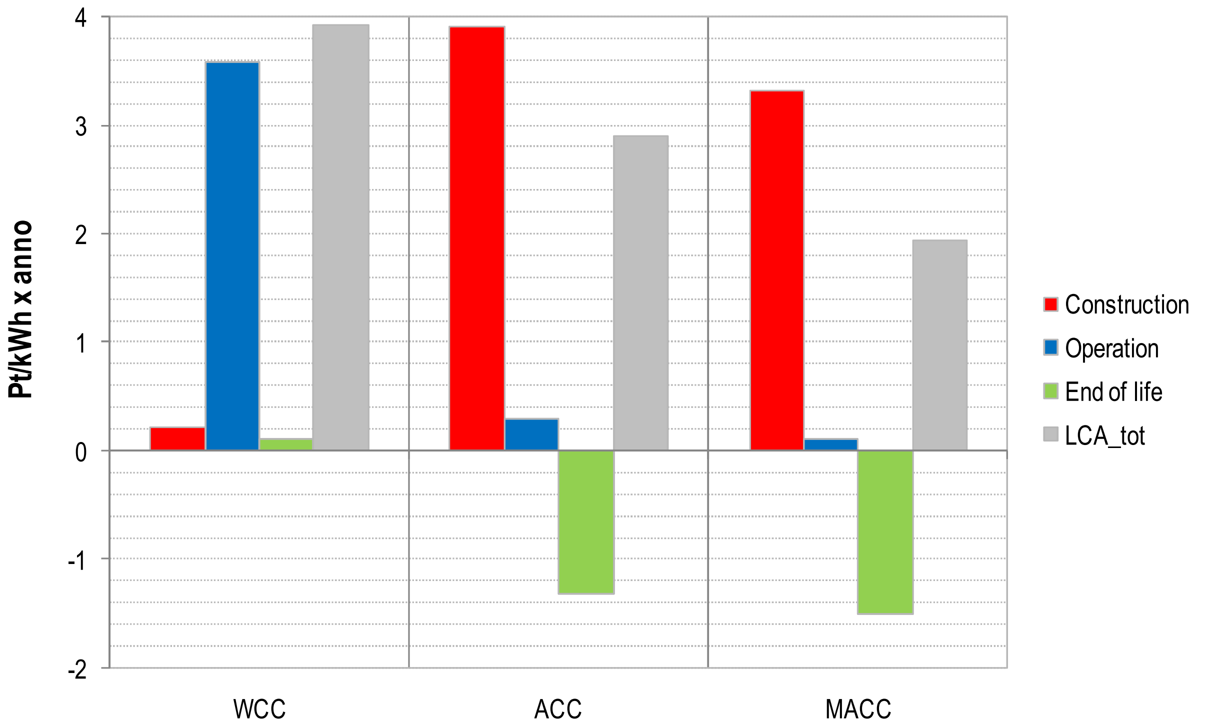

Fig. 6 - Overall impact of the condensers (Ecological Scarcity 2006 method)

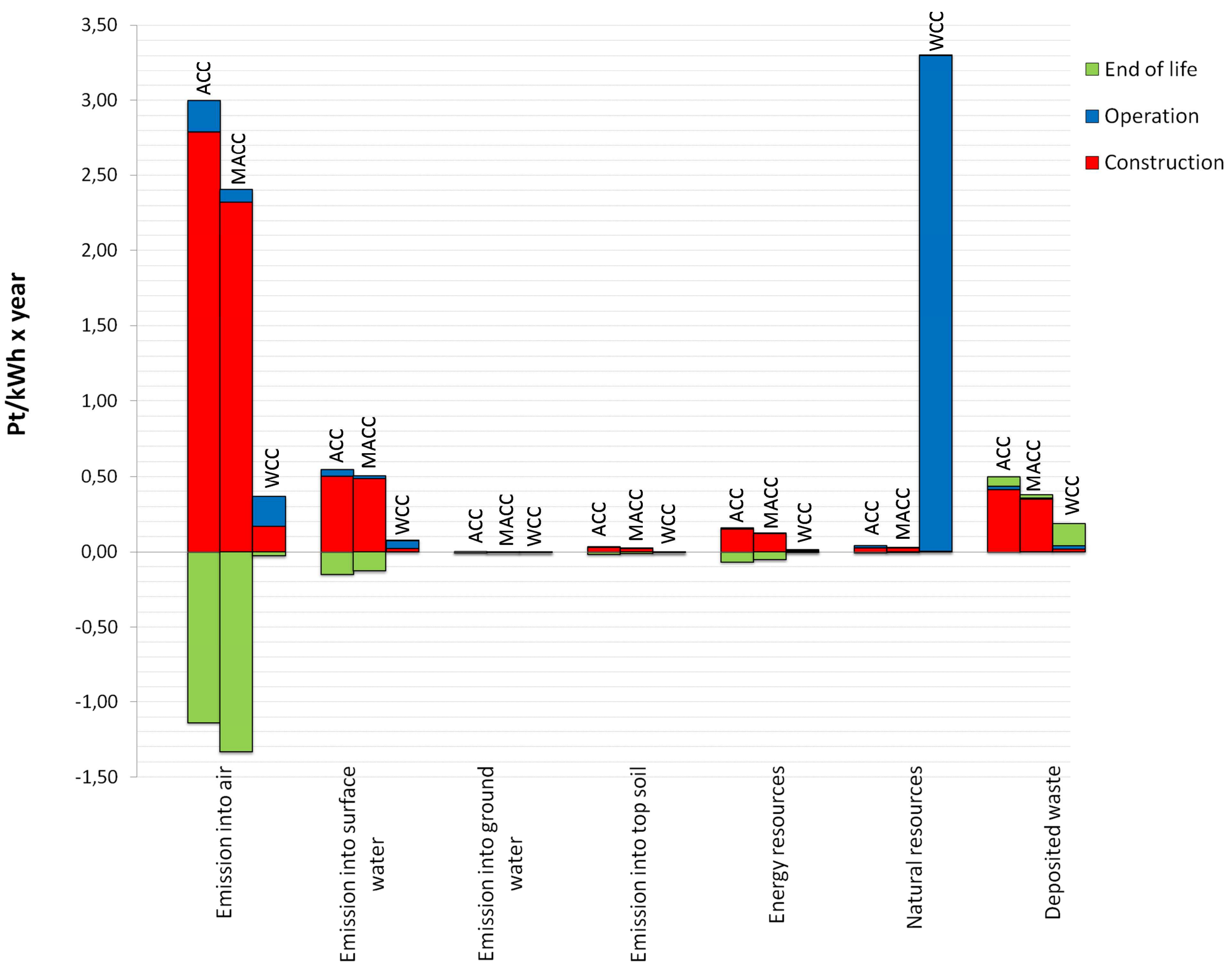

Fig. 7 - Breakdown by category of the overall life cycle impact (Ecological Scarcity 2006 method)

Tab. 5 - Ecological Scarcity 2006 parameters [34]

Water stress	SR	SR used in calculation	W	Eco-factor (EP/m^3)
Low	<0.1	0.05	0.0625	24
Moderate	≥0.1 <0.2	0.15	0.563	220
Medium	≥0.2 <0.4	0.3	2.25	880
High	≥0.4 <0.6	0.5	6.25	2,400
Very high	≥0.6 <1	0.8	16.0	6,200
Extreme	≥1	1.5	56.3	22,000

The categories "deposited waste" and "emission into surface water" present an appreciable cumulative contribution on the overall impact of each condenser (6.7 % for the WCC, 31.0 % for the ACC, and 38.8 % for the MACC), and the category "energy resources" slightly contributes to the ACC and the MACC impact (respectively, 3.2 % and 3.8 %) and it is negligible for the WCC (contribution equal to 0.4 %). The same applies for the categories "emission into ground water" and "emission into top soil" that contribute to the impact of the three condensers with a share lower than 1 %.

Discussion

The assessment through the IPCC 2007 and Ecoindicator 99 methods shows that the WCC is characterized by an impact significantly lower than the one of the ACC and the MACC, essentially as a consequence of the low impact associated to its construction phase. The materials used for the construction of the WCC, in fact, are mainly plastics (Polyethylene, Polyester, PVC, etc.) and glass fiber reinforced plastic, which have a significantly lower impact per unit of mass and a lower specific weight that implies a high reduction of the impact associated with the transports. On the other hand, for the construction of the ACC and the MACC, ferrous and non-ferrous metals (mainly steel and aluminum) are used, determining a major contribution of the construction and transport activities, since they are characterized by a high impact per unit of mass and by a higher specific weight. The operation phase emerges as a key contributor to the overall environmental impact of the WCC, for which it is comparable with the impact of the construction phase and represents a 40–60 % of the total (depending on the evaluation method used). Regarding the dry-cooled condensers, instead, this phase has a minor contribution to the overall impact (about 5–10 %). The reason of this result is the treatment of complete softening to which water is subjected before reintegration in the cooling water circuit, which is responsible for a considerable impact in addition to the one associated with fan and auxiliary power consumption. Looking at Ecoindicator 99 method results, the most relevant categories for each condenser are "carcinogens", "respiratory inorganics" and "fossil fuels". These categories are responsible for the difference between the MACC and the ACC (reduction approximately 70–80 %) and, since the Ecoinvent datasets used in SimaPro were the same (e.g., the dataset "reinforcing steel, at plant" was used for the supporting steel structure both of ACC and MACC), this is a consequence of the optimization of the MACC prototype arrangement.

The Ecological Scarcity 2006 method show a different trend in results, since the overall impact is strongly influenced by the freshwater consumption in medium water stress conditions. The impact of the WCC results about doubled compared to the one of the MACC and 1.35 times higher than the

Tab. 6 - Overall impact variation from scenario 1 to scenario 2

Method	Var. Scenario 1 – Scenario 2		
	WCC	ACC	MACC
IPCC 2007	+17.1%	+17.4%	+29.3%
Ecoindicator 99	+12.6%	+11.9%	+22.7%
Ecological scarcity 2006	+0.7%	+7.8%	+14.7%

impact of the ACC. This result is due to the operation of the WCC and, in particular, to the category "natural resources", which accounts for 92.1 % of the impact of this phase. This evidence confirms the key role of cooling water consumption in regions suitable for CSP plant and suggests to properly take into account this issue when carrying out environmental analyses. Therefore, even if the materials used in WCC construction resulted more environmentally-friendly than the ones used for dry-cooled condensers, the operation phase emerged as the key issue for choosing the best cooling solution in CSP plants applications.
In general, the LCA analysis indentifies the MACC as a better cooling solution compared to the ACC, an evidence far from being obvious since the two condensers have similar characteristics, i.e. same construction materials as well as similar amount of materials used for analogous components.
Looking at the variation of the results from scenario 1 to scenario 2, it is observed a significant increase due to the transport modes characterized by an higher environmental impact. Moreover, it emerges that the impact assessment methods are differently affected by the transport mode choice, with Ecoindicator 99 and Ecological Scarcity 2006 ones having less variability (Table 6).
Disregarding the results of the Ecological Scarcity 2006 method, which are significantly affected by the water consumption, it is also worth noting that the overall impact of the MACC is more affected by logistic (e.g., distances involved in the construction phase) and transport mode choices, which thus represent key issues for a further reduction of the environmental pressures related to its life cycle.

Conclusions

CSP is considered one the most promising technologies for power generation. Most of the existing CSP plants are equipped with WCCs but, due to the issue of water scarcity and to the several projects that aim at the development of CSP plants in desert areas, a more extensive use of ACCs is predictable.
The MACCSol research project, which received co-funding under the EU's 7th Framework Programme, addressed the development of an innovative modular air-cooled condenser (MACC) able to reduce the typical issues of conventional ACCs.
A comparative LCA analysis was carried out to counterpose a specific MACC configuration to conventional steam condensers, using "conventional" impact assessment methods (IPCC 2007, Ecoindicator 99) and also accounting for freshwater consumption – one of the main environmental issues of CSP plants – through the Ecological Scarcity 2006 method. The MACC condenser came out as a better cooling solution compared to conventional ACC according to all the assessment methods used, due to the significant reduction of power consumption related to the operation phase and to the optimization of the MACC condenser layout, which generates an appreciable decrease of the impact associated with the condenser construction.
Taking into account freshwater consumption-related impact in conditions of limited availability of the resources (the site of operation considered is the south of Spain), the MACC emerged as the best cooling option: its impact was halved compared to the WCC and 1.35 times lower compared to the ACC. This high impact reduction is due to the decrease

occurred in the categories natural resources (compared to the WCC), which accounts for the water consumption, and emission into air (compared to ACC). Therefore, even if the advantages related to the use of dry-cooled condensers in conventional power plants have to be properly evaluated, their application in regions suitable for CSP plants is desirable and, among the different options, the innovative MACC seems to be better than conventional ACCs. Furthermore, a first evaluation (MACCSol 2014-1) showed that the environmental advantages of MACC result higher with the increase in water scarcity. In fact, varying the water stress from medium to high, the impact of the WCC is expected to increase up to a +100 %, while the impact of the MACC is expected to vary less (± 15–20 %), remaining at the same time considerably lower than the one of the conventional ACC. In a global context characterized by several projects that aim to develop CSP plant in desert areas, therefore, the use of the MACC could significantly contribute to the reduction of the life cycle impacts related to power generation through this kind of plants. Moreover, the analysis showed that the life cycle impact of the MACC could be further reduced through a proper planning of the transport activities, thus contributing even more to the environmental sustainability of CSP plants.

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