

Environmental and energy assessment of a small-scale solar Organic Rankine Cycle trigeneration system based on Compound Parabolic Collectors

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Abstract

During the last years, combined cooling, heating, and power (CCHP) systems have drawn a lot of attention thanks to their low greenhouse gas (GHG) emissions, high efficiency and cost benefits. Considering the increasing interest on sustainability assessment of innovative energy generation technologies, in this paper a life cycle assessment of an innovative small-scale solar Organic Rankine Cycle (ORC) trigeneration plant is performed.

The plant under investigation is composed of a 50 m² Compound Parabolic Collectors (CPC) solar field, a 3 m³ diathermic oil storage tank, a 3.5 kW_e ORC plant and a 17 kW_e absorption chiller. After the set-up of the inventory data of the different subsystems, a sensitivity analysis of the environmental and energy performance of the plant has been conducted by varying: (i) the system adjustment parameters; (ii) the size of the solar field and the consequent solar multiple index of the plant; and (iii) the organic working fluid of the ORC unit. Results of the analysis confirmed that the Life Cycle Assessment (LCA) is of paramount importance for the appropriate selections of component specifications and operating conditions of the integrated system. In particular, the investigation has revealed that the variation of the adjustment parameters brings to slight modifications of the energy performance and has a limited impact on the environmental output whilst the proper selection of the working fluid and the size of the solar field can result in an appreciable environmental optimization of the whole plant.

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Keywords

renewable energy; Concentrated Solar Power technologies; ORC system; micro combined cooling heating and power systems; life cycle assessment

Nomenclature

A	area of the collector [m^2]
a_0	first order efficiency coefficient [$\text{W}/\text{m}^2 \cdot \text{K}$]
a_1	second order efficiency coefficient [$\text{W}/\text{m}^2 \cdot \text{K}$]
C_i ($i=1, \dots, 7$)	i-th configuration
CHP	Combined Heating and Power
CCHP	Combined Cooling, Heating and Power
COP	Coefficient Of Performance
CPC	Compound Parabolic Collector
CSP	Concentrated Solar Power
EPBT	Energy Pay Back Time
ETC	Evacuated Tube Collector
G_b	direct radiation on collector plane [W/m^2]
G_d	diffuse radiation on collector plane [W/m^2]
GWP	Global Warming Potential
h_{abs}	operating hours of the absorption chiller [h]
h_{ORC}	operating hours of the ORC unit [h]
HSW	hot sanitary water
HTT	High Temperature storage Tank
IAM	Incident Angle Modifier
LCOE	Levelized Cost Of Energy
LFR	Linear Fresnel Reflector
LTT	Low Temperature storage Tank
K_θ	Incident Angle Modifier for direct radiation
K_d	Incident Angle Modifier for diffuse radiation
\dot{m}_c	mass flow rate of the cooling water [kg/s]
\dot{m}_f	mass flow rate of the organic fluid [kg/s]
P_e	Electrical Power [kW_e]
P_c	Cooling Power [kW_e]
P_t	Thermal Power [kW_t]
P_{abs}	cooling power output from the absorption chiller [kW_e]
$P_{\text{abs,in}}$	inlet thermal power to the absorption chiller [kW_t]
$P_{\text{ORC,el}}$	electrical power produced by the ORC unit [kW_e]
$P_{\text{ORC,out}}$	outlet thermal power from the ORC unit [kW_t]
$P_{\text{ORC,in}}$	inlet thermal power to the ORC unit [kW_t]
$P_{\text{SF,in}}$	inlet power to the solar field [kW]
$P_{\text{SF,out}}$	outlet thermal power from the solar field [kW_t]
PTC	Parabolic Trough Collector
Q_{loss}	heat losses at the receiver [kW_t]
SM	Solar Multiple
TES	Thermal Energy Storage
T_a	ambient air temperature [$^\circ\text{C}$]
T_{av}	average temperature [$^\circ\text{C}$]
T_{in}	inlet temperature of the cooling water at the condenser [$^\circ\text{C}$]

82	T_m	mean temperature of the fluid in the collector [°C]
83	T_{out}	outlet temperature of the cooling water at the condenser [°C]
84	$T_{ORC,off}$	lower bound temperature set-point of the TES [°C]
85	$T_{ORC,on}$	upper bound temperature set-point of the TES [°C]
86	$T_{TES,av}$	average temperature of the TES [°C]
87	Δh_e	actual specific enthalpy difference across the expander [kJ/(kg K)]
88	Δh_p	actual specific enthalpy difference across the pump [kJ/(kg K)]
89	ΔT_h	hot period working temperature range of HTT-ORC inlet [°C]
90	ΔT_c	cold period working temperature range of HTT-ORC inlet [°C]
91	ΔT_m	mid seasons working temperature range of HTT-ORC inlet [°C]
92	kW_{el}	electric kW
93	kW_{th}	thermal kW
94	kW_c	cooling kW
95		

96 **Greek symbols**

97	α	solar elevation angle
98	β	absorptance coefficient
99	ε	emittance coefficient
100	η_{el}	electrical efficiency
101	$\eta_{e,ORC}$	ORC unit electrical efficiency
102	$\eta_{glob,CCHP}$	CCHP global efficiency
103	η_m	mechanical efficiency
104	η_{opt}	maximum optical efficiency
105	$\eta_{ORC,el}$	ORC unit electrical efficiency
106	$\eta_{ORC,th}$	ORC unit thermal efficiency
107	η_{SF}	overall conversion efficiency of the solar field
108		

109

110

1. Introduction

Among the key instruments to curb CO₂ emissions and guarantee a sustainable development, the use of locally available renewable sources and multi-purpose energy systems has a great potential. In particular, use of solar energy in decentralized energy systems is foreseen to play a prominent role in mitigating the global warming scenario of the present century [1]. Beside the conventional solar thermal technologies and photovoltaic systems, Concentrated Solar Power (CSP) systems are attracting a lot of attention and are gradually moving their application field from large-scale to small and medium scale plants. In particular, CSP systems find a new scope in the distributed power generation through the CHP and CCHP applications [2]. Indeed, the concentration of the sun light allows to achieve higher heat grade capable to feed more elaborated processes such as cooling and power generation thus extending the applicability of solar thermal energy. As a consequence of this perspective, the application of the main CSP technologies, such as Parabolic Trough Collector (PTC), Solar Power Tower (SPT), Parabolic Dish System (PDS), Linear Fresnel Reflector (LFR) and Compound Parabolic Collector (CPC) [3], have been object of many studies. For example, their combination with Organic Rankine Cycle systems is attracting a lot of interest also at small scale and many researchers have focused on them. . The optimization of this coupling has been studied with regard to the appropriate sorting of working fluids [5] also considering their effect on the selected expansion machine [6]. Moreover, different systems have been designed and tested both fully solar-powered as in the case of small PTC solar fields coupled with scroll expander [7] or single-cylinder expander [8] for a power production of few electric kW and hybrid large-scale plants [9]. With reference to the small-scale, Freeman et al [11] investigated the appropriateness of PTC and ETC solar technologies in ORC CHP applications. In another work [12], the same authors emphasized the impact of the thermal energy storage (TES) on the performance of a residential solar-ORC CHP system in UK. Instead, Boyaghchi et Heidarnajad [13] conducted a mathematical study consisting in the multi-objective optimization of a solar powered CCHP system based on a 2.7 kW_e ORC unit and an ejector refrigeration cycle. With respect to trigeneration systems, Karellas and Braimakis [14] modelled a CCHP plant composed of an hybrid biomass-solar ORC coupled with a vapor compression chiller. Cioccolanti et al [15], instead, focused their attention on a solar ORC trigenerative system, composed of a 50 m² CPC solar field, a 3.5 kW_e ORC unit and a 17.6 kW_e Yazaki absorption chiller, and assessed the energy performance of the plant by varying some design and operating parameters.

The growing interest towards solar power generation technologies and, in particular, to solar CHP and CCHP ORC systems makes of paramount importance the thorough analysis of the environmental impact of such systems. In general, the environmental sustainability of a CHP system is assessed to comparatively define its overall environmental performance and potential benefits compared to traditional technologies and separate thermal and electrical energy production.

For example, Ruzzenenti et al. [16] conducted a life cycle analysis (LCA) and an exergy life cycle analysis regarding micro scale geothermal-solar ORC plants for CHP use. Zhai et al. [17] studied solar aided coal-fired power systems by the comparison of the LCA at different configurations from the plain coal-fired power system to the solar aided system with or without the thermal energy storage. In [18], instead, the LCA of ORC CHP systems was referred to the geothermal energy

source and examined the different environmental issues varying the organic working fluid involved in the ORC power generation unit. Tagliaferri et al. [19], developed a LCA of the 2 MW_e/8 MW_{th} biomass power plant installed at Heathrow airport. The considered ORC installation represents a more environmentally friendly solution respect to any alternative steam turbine by virtue of the major efficiency of the ORC. In their work, Wang et al. [20] proposed an LCA optimization methodology for a natural gas CCHP system assisted by photovoltaic modules and solar thermal collectors for the electricity and the heat production, respectively. In this study, the analysis compared the following electrical load and the following thermal load operational strategies of the plant and indicated the latter as the more effective. Safaei et al. [21], instead, proposed a methodological framework where the benefits of the distributed generation in terms of its environmental impacts in buildings are emphasized. In particular, the authors highlighted that the design and the operational strategies cannot be fortuitous, but the proper trade-off needs to be identified considering the proper geographical frame, especially for those technologies depending on meteorological conditions such as solar. In another work [22], the LCA regarding a hybrid CHP system composed of solar PV, Stirling engine and battery showed that the environmental impact of the system is much lower than the separate production and supply of power and heat. The most effective parameters were the size of the household and the operation of the Stirling engine.

With reference to the concentrating solar systems, Lamnatou et al. [23], at the end of 2017, presented a review of LCA studies applied to the different technologies considered such as concentrating solar power, concentrated photovoltaic, and concentrated photovoltaic/thermal. The results of this work demonstrated the lack within the present literature of appropriate and extensive studies regarding small-scale CSP systems applied to buildings for multiple final applications. Indeed, most of the studies referred to large scale plants. For example, Tripanagnostopoulos et al. [24] determined that hybrid photovoltaic/thermal CHP solar systems have a better environmental impact compared to standard photovoltaic modules.

Lechon et al. [25] evaluated the environmental impacts of a 17 MW central tower and a 50 MW PTC solar power plant. Considered the functional unit of 1 kWh of electricity, the avoided impact in terms of GWP have been determined.

In [26] the environmental impact of a 103 MW PTC concentrating solar power plant located in Daggett, CA, has been analyzed in terms of life cycle greenhouse gases, cumulative energy demand and energy payback time. Furthermore, the impacts related with the choice of some key operative and design parameters have been highlighted.

A further LCA of a 50 MW CSP power plant based on PTCs and a two-tank configuration has been developed by Heath et al. [27] at the National Renewable Energy Laboratory.

Piemonte et al. [28], instead, presented the LCA of a molten salt CSP power system combined with a biomass back-up burner developed and built at ENEA research center in Italy. The environmental issues of the solar power system have then been compared with those of conventional oil and gas power plants and the authors have emphasized the benefits of the solar plant compared to the fossil fuels-based systems.

While there are several works in literature regarding the life cycle analysis of ORC power, CHP and CCHP systems, and large size CSP power plants, to the best of the authors' knowledge no many articles referred to small scale CSP systems coupled with ORC units for cogeneration applications and, especially, no articles at all referred to such systems for trigeneration purposes by means of absorption chillers. Hence, the aim of this study is to identify the environmental hotspots of a small-scale solar CCHP system, previously simulated by some of the authors [reference di nuovo], through performing a comprehensive life cycle assessment approach. Furthermore, this study evaluates to what extent design and operating parameters namely, (i) the working temperature range of the hot storage tank; (ii) the solar multiple of the plant; and (iii) the organic working fluid of the ORC unit, affect the environmental performance, damage categories and sustainability indicators corresponding to CCHP system studied.

Thus, the paper is organized as follows: after the introduction, materials and methods are presented in Section 2 and, then, a representation of results and their discussion is provided in Section 3. Eventually, the last section summarizes the main conclusions.

2. Materials and methods

2.1 Description of the system and its energy model

As mentioned above, the object of the present environmental analysis is an experimental trigenerative solar-powered system designed and built by some of the authors [15,29,30]. The plant is located in the city of Orte in the north of Rome (Italy) and it consists of the following main components: a 35 kW_t solar thermal plant composed of Compound Parabolic Collectors (CPC) patented and manufactured by Kloben [31], a 3.5 kW_e regenerative Organic Rankine Cycle power system manufactured by Newcomen [32] and a 17.6 kW_c absorption chiller by Yazaki Energy Systems [33]. In turn, the latter is connected to an evaporative cooling tower to dispose the low temperature heat to the ambient. Eventually, two 3 m³ tanks are included into the plant to decouple the solar field from the ORC unit and the latter from the absorption chiller. In particular, diathermic oil is used in the High Temperature Tank (HTT) and water in the Low Temperature Tank (LTT). Figure 1 reports a scheme of the trigeneration plant under investigation:

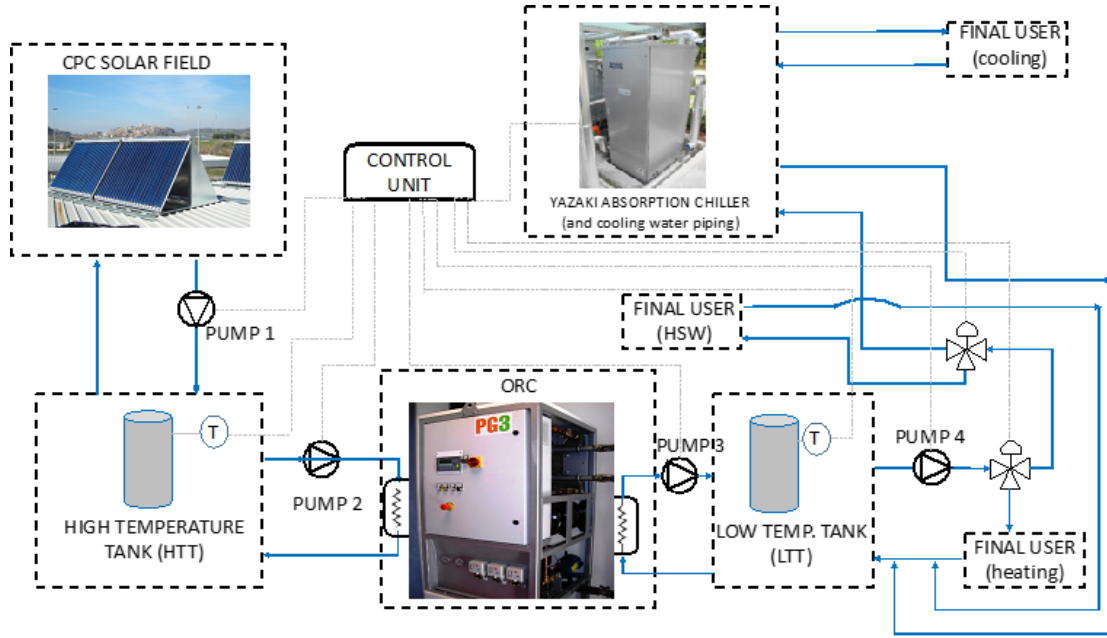


Figure 1 Scheme of the trigeneration plant under investigation

As regards the solar field, it consists of twelve solar collectors, ten SKY PRO 22 and two SKY PRO 20 [34], for a total collecting area of about 50 m². The considered collectors are able to achieve heat fluid temperatures up to 190°C by means of copper tubes for high vacuum applications. Therminol 62 is used as thermal vector thanks to its high thermal stability up to 325°C and low vapor pressure [35]. With reference to the ORC system, the expander is a three radial cylinders alternative engine conceived for operating with R134a as working fluid. However, since the absorption chiller requires higher temperatures for its proper operation, R245fa has been used in the present system. Indeed, the critical temperature of R245fa is higher than the 100-150 °C operating temperature range of the considered solar-ORC system. With respect to the latter, the fluid released its heat to the absorption chiller which, according to Yazaki technical data [33], provides cold water at a nominal temperature of 7 °C with a Coefficient of Performance (COP) of 0.7 (at 88 °C inlet hot water temperature). In any case, the system is able to work with acceptable performance until a minimum inlet hot water temperature of 70°C.

The overall system has been modelled in TRNSYS [36] to assess the dynamic energy performance of the plant. In particular, the following TRNSYS library components have been used: Type 71 for the CPC solar field; Type 4 for both the HTT and the LTT; Type 107 for the absorption chiller; Type 510 for the evaporative cooling tower. The ORC, instead, has been modelled by means of an ad-hoc subroutine developed in Matlab [37] and called by means of Type 155. Based on the climatic zone of Orte and according to the Italian decree 412/93 [32], the heating season has been fixed between 1st of November and 15th of April. On the contrary, the cooling one has been assumed from 1st of June to 30th of September.

With regard to the energy production, the collected thermal energy from the CPC solar field is calculated as in Equation 1:

$$P_{SF,out} = A \cdot (\eta_{opt} \cdot (G_b \cdot K_\theta + G_d \cdot K_d) - a_0 \cdot (T_m - T_a) - a_1 \cdot (T_m - T_a)^2) \quad (1)$$

where A is the area of the collectors, G_b and G_d the direct and diffuse radiation on the collectors' plane, K_θ and K_d the Incident Angle Modifier (IAM) for direct and diffuse radiation respectively, T_m the mean temperature of the fluid in the collectors, T_a the ambient air temperature, η_{opt} the maximum optical efficiency, and a_0 and a_1 two coefficients depending on the type and the model of the collectors. With reference to the considered collectors, such coefficients are 0.974 and 0.005 $W/m^2 \cdot K$ respectively.

As regards the ORC unit the electrical and thermal power output can be expressed as in Equations 2 and 3:

$$P_{ORC,el} = \dot{m}_f \cdot [\eta_m \cdot \eta_{el} \cdot \Delta h_e - \Delta h_p / (\eta_m \cdot \eta_{el})] \quad (2)$$

$$P_{ORC,out} = \dot{m}_c \cdot c_{p,c} \cdot (T_{out} - T_{in}) \quad (3)$$

With respect to Eq. 2, \dot{m}_f is the organic fluid flow rate, η_m and η_{el} are the mechanical and electric efficiencies equal to 95% and 90% respectively (assumed equal for both the pump and the expander), Δh_e and Δh_p are the actual specific enthalpy difference across the expander and the pump.

In Eq. 3, instead, \dot{m}_c is the water flow rate, $c_{p,c}$ is the specific heat of the water and T_{out} and T_{in} are the outlet and inlet water temperatures at the condenser.

Eventually, the cooling power generated by the absorption chiller is evaluated as follows:

$$P_{abs} = P_{abs,in} \cdot COP \quad (4)$$

where $P_{abs,in}$ is the thermal power supplied from the LTT to the chiller.

Further details on the model can be found in [reference ECM o APEN, dove ci sono].

Once the energy performance of the system is assessed, such are used within the LCA model here developed.

Similarly to the previous work of some of the authors [15] aimed at investigating the energy performance of the system with varying operating and design parameters, in this paper the sensitivity analysis of its environmental impact is performed for different configurations of the system thematically grouped into three scenarios. Each scenario considers the variation of a selected operating or design parameter, given fixed the others, and aims at evaluating its influence on the environmental and energy performance of the plant. More precisely, the base configuration (C1) corresponds to the most performing configuration of the system obtained in [15] by varying the working temperature range of the tanks only. Table 1 reports the main specifications and operating conditions of the plant in the base configuration C1:

Table 1 – Component specifications and operating conditions of the base configuration C1

C1 design specifications	Value	C1 operating conditions	Value
Solar Collectors Area	50 m ²	ΔT_h	170-160 °C
ORC System	3.5 kW _e	ΔT_c	120-110 °C
Absorption chiller	17.6 kW _e	ΔT_m	160-135 °C
Pumps	30-120 l/min; 10 m*	CPC-HTT mass flow rate	7000 kg/h
HT Storage Tanks	3 m ³	HTT-ORC mass flow rate	1800 kg/h
LT Storage Tanks	3 m ³	LTT_abs-2 mass flow rate	3600 kg/h

Temperature @Terminals	Winter: 30°C; Summer: 15°C	LTT_abs mass flow rate	4320 kg/h
Organic working fluid	R245fa	Local coordinates	42° 45' 74.41'' N 12° 38' 69.84'' E

2.2 LCA methodology

LCA as a holistic approach for comprehensive environmental evaluation of the energy system, is implemented in this study following ISO standards (ISO14040:2006, ISO14044: 2006) [38,39]. In general, this approach is globally required to improve performance of products or services, to plan strategy or design/redesign process, to select relevant indicators and to support marketing or performance claims based on the environmental aspects and possible impacts connected with a product. A LCA typically includes four stages: the goal and scope definition, the inventory analysis, the life cycle impact assessment and the interpretation of results [40].

For what concerns the goal of the present study, it is twofold: (i) to identify and quantify the environmental profile of the innovative trigeneration system conceived for residential applications and (ii) to evaluate the impact of varying design and operating parameters on its environmental and energy performance. Hence, the final aim of this analysis is to provide worthwhile insights into the merits and demerits of similar distributed energy systems and to serve as a useful analytical and decision support tool to design and construct a small-scale trigenerative ORC at residential level. The main audience of the study are policymakers who looking at environmental standards for promoting and achieving a sustainable development. The system is assessed following a cradle to gate approach and considering 1 kWh of equivalent primary energy (1 kWh_{PEP}) as functional unit because capable of expressing the energy production through a unique term. The system boundaries include extraction, construction and consumption of all material and energy used in the life cycle of solar collectors, ORC and absorption chiller systems integrated into a unique trigeneration system as shown in Figure 2. Instead, decommissioning and disposal of components are excluded due to lack of data.

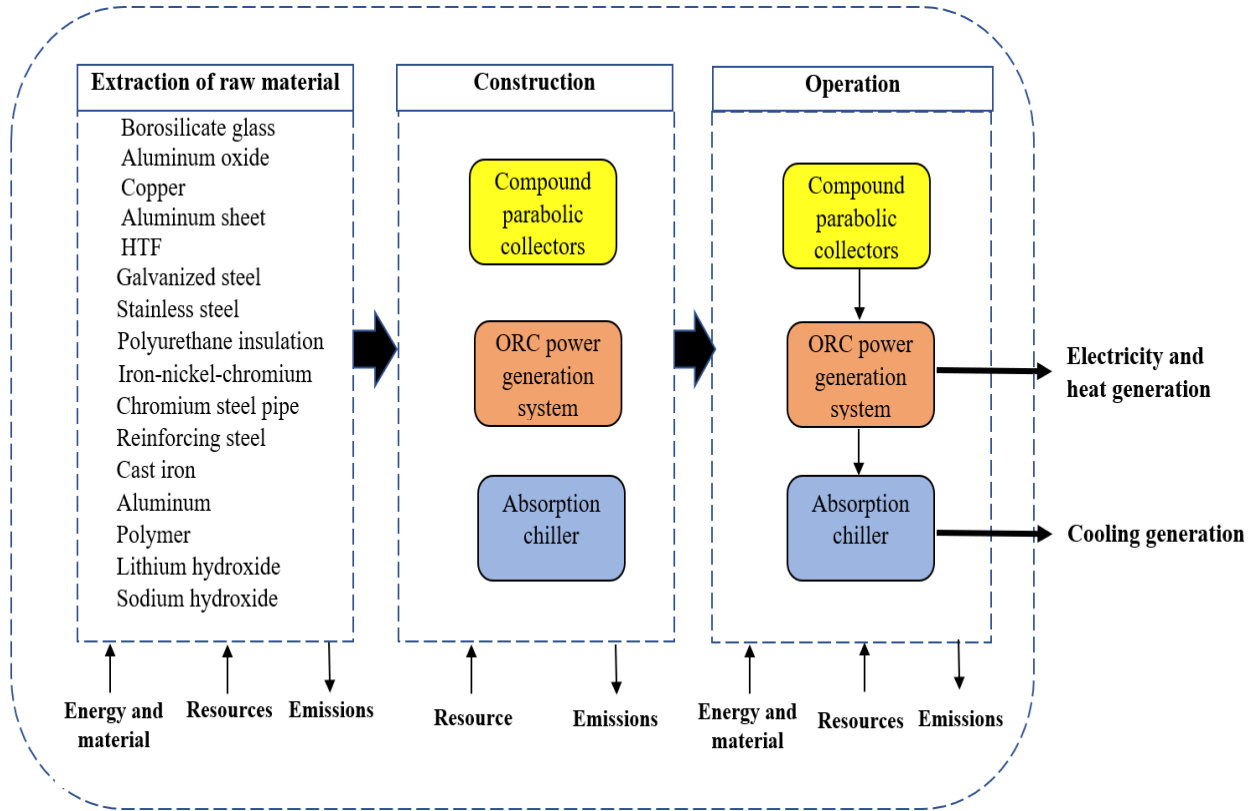


Figure 2. System boundary of the trigeneration system

2.2.1 Data sources and inventory

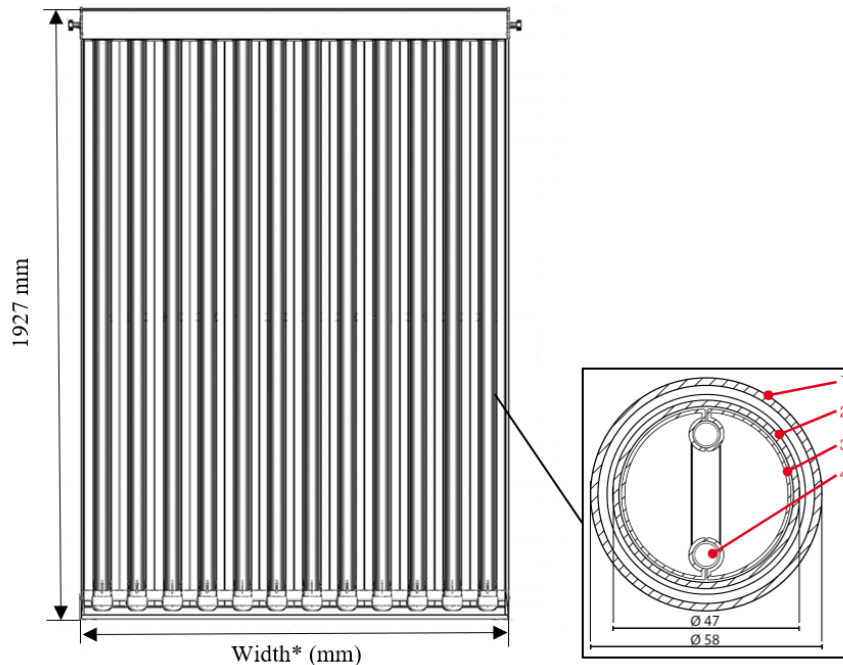
Based on the system boundaries, the life cycle inventory data are collected for the three main subsystems, namely the solar collectors, the ORC system and the absorption chiller.

Solar plant

The inventory data of the solar plant components are provided by Kloben company [41] leader in the manufacturing of this solar technology in Italy. Table 2 reports the considered technical data of the solar collectors used (ten SKY PRO 22 and two SKY PRO 20) while Figure 3 illustrates the cross-section of the solar collectors under analysis to better appreciate their composition.

Table 2 Technical data of the solar collectors under investigation

Type of collector	Vacuum tubes (No.)	Gross surface area (m ²)	Open surface (m ²)	Absorption surface (m ²)	Width (mm)	Length (mm)	Height (mm)	Empty weight (kg)	Liquid content (L)	Collector attach (mm)
SKY PRO 20	20	4.27	3.81	5.17	2222	1927	116	85	2.93	18
SKY PRO 22	22	4.69	4.19	5.69	2442	1927	116	94	3.22	18



*2222 mm (SKY PRO20), 2442 mm (SKY PRO22)

- 1- Borosilicate glass outer tube
- 2- Internal tube with Al-N/Al selective material
- 3- Aluminum absorber (Al_2O_3)
- 4- U-shaped copper pipe

Figure 3 cross-section of the solar collectors under analysis [ref]

However, due to the lack of some data in the software database the diathermic oil used in the real application, namely Therminol 62 [di nuovo stessa reference], is substituted by a mixture of 73.5% diphenylether (w/w) and 26.5% phenol (w/w) according to the assumptions applied in [42].

ORC system

For what concerns the 3.5 kW_e ORC unit, the materials used for its construction have been estimated by an accurate analysis of the plant installed in Orte. As regards the working fluid, an amount of 11.56 t/MW_e has been considered according to a previous LCA study on ORC systems [18] which estimated the required amount of working fluid per power plant capacity. In terms of environmental impact, R-245fa (1,1,1,3,3 Pentafluoropropane) has a Global Warming Potential equals to 1050 and a 7-year life time [43]. Its emissions are included and calculated in the model considering an annual leakage rate of 2% [18,44].

Absorption chiller

According to the information provided by Yazaki company, the outer structure of the main components of the absorption chiller, namely the evaporator, the condenser, the absorber and the generator, are made of stainless-steel whilst copper is used for the heat transfer tubes. The weight of these materials is calculated based on the assumptions adopted in [45]. The energy consumption for the operation of the absorption chiller, instead, is calculated considering the working hours of

the pumps. As regards the solution, the considered absorption chiller makes use of a mixture of water and lithium bromide where the latter acts as absorbent medium. In particular, the lithium bromide solution is the result of the reaction between the lithium hydroxide (LiOH) and the hydrobromic acid (HBr) [46], as reported in equation 1:



According to the absorption chiller requirements, the desired lithium bromide solution accounts to 31 kg as quoted by Yazaki company [reference]. Since the production data of the hydrobromic acid is not reported in the software database, it has been assumed that the lithium bromide solution consists of lithium hydroxide only. Because lithium bromide solution has high corrosion potential and could lead to absorption chiller performance reduction, a corrosion inhibitor is added to the solution. In this study, according to [45], a sodium molybdate based corrosion inhibitor is considered. More precisely, sodium hydroxide and sodium molybdate are substances participated in production of this inhibitor [45]. As concerns the amount of such substances, the mass of sodium hydroxide has been calculated considering a stoichiometry reaction while that of sodium molybdate has been neglected due to lack of data.

Eventually, independently from the subsystem the extraction phase of the raw materials used for their construction as well as the processing phase of fuels and electricity consumed have been obtained from the Ecoinvent database in SimaPro software [47]. Table 3 reports the life cycle inventory of the trigeneration system under analysis considering a life time of 20 year.

Table 3. Life cycle inventory of the trigeneration system under analysis.

Plant component/Commodity	Material/Energy	Quantity
CPC solar plant components		
Evacuated tubes	Borosilicate glass (kg)	3306.9
	Aluminum oxide (kg)	3728.5
	Copper (kg)	8.5
	Aluminum sheet (kg)	2850
Heat transfer fluid	Diphenylether 73% (Wt %) (kg)	2856.3
	Phenol 26.5% (Wt %) (kg)	1036.8
Supporting kit	Galvanized steel (kg)	131
Hot temperature tank	Stainless steel (kg)	120
	Polyurethane insulation (m)	1.02
Pump	Stainless steel (kg)	1.8
	Cast iron (kg)	13.9
Pipeline	Stainless steel (kg)	196.72
ORC components		
Evaporator	Copper (kg)	64.6
	Iron-nickel-chromium alloy (kg)	7.3
	Stainless steel (kg)	1
Condenser	Stainless steel (kg)	87.5
	Chromium steel pipe (kg)	22.5
	Iron-nickel-chromium alloy (kg)	12.5
Expander	Stainless steel (kg)	328.6
	Reinforcing steel (kg)	198.9
	Chromium steel pipe (kg)	71.5
	Copper (kg)	19.3

	Aluminum (kg)	10.9
	Iron-nickel-chromium alloy (kg)	5.8
	Polymer (kg)	4.8
Pump	Stainless steel (kg)	0.47
	Cast iron (kg)	3.6
Pipeline	Stainless steel (kg)	147.96
Working fluid	R245fa (kg)	112

Absorption chiller components

Evaporator, condenser, absorber and generator	Stainless steel (kg)	168
	Copper (kg)	74.75
Lithium Bromide solution	lithium hydroxide (kg)	4.3
Corrosion inhibitor	Sodium hydroxide (kg)	0.1
Pump	Stainless steel (kg)	2
Pipeline	Stainless steel (kg)	147.96
	Cast iron (kg)	15.8
Low temperature tank (kg)	Stainless steel (kg)	120
	Insulation (m)	1.02
Water	Tap water (kg)	6000
Electricity	Electricity (kWh)	2524.5

2.2.2 Sensitivity analysis

In order to evaluate the impacts of varying design and operating parameters on the environmental and energy profile of the trigeneration system, a sensitivity analysis has been developed based on three thematic scenarios consisting of seven different configurations totally. In particular, the first scenario aims at evaluating the effects of the variation of some system adjustment parameters, the second one aims at assessing the effects of three different solar field sizes which determine the solar factor of the system and the third scenario evaluates the effects of employment of three different working fluids in the ORC subsystem. Each scenario comprises three configurations while configuration 1, as base case, is included in all the considered scenarios.

With respect to Scenario 1, the variation of the working temperature range of the HTT is considered as driver. The performances of the system, indeed, are significantly affected by the temperature at the HTT and the system operation requiring a fixed certain temperature range. When the temperature at the HTT storage tank reaches the upper bound the ORC switches on the mode when it goes down the lower value of the range it is switched off. Hence, in Scenario 1 the working temperature ranges have been varied similarly to the previous work by Cioccolanti et al. [15].

As regards Scenario 2, the size of the solar plant is considered as driver. The solar multiple (SM), which corresponds to the ratio between the area of the solar field considered in the project and the area of the solar field corresponding to the power feed of the ORC unit at its nominal operating conditions, has been varied in the range 1.42-2.85.

Eventually, in Scenario 3, the impact of two other different low-GWP working fluids, namely Neopentane and R245ca, has been assessed and compared to that of R245fa as in the base configuration C1. As reported in [18], these two low-GWP working fluids represent the best compromise between good energy performance of low temperature ORC and very low environmental impact in terms of GWP.

In order to compare the environmental performance of the different configurations, the energy outputs are presented by the equivalent primary energy productions [48]. In particular, the

equivalent primary energy of the electricity produced is calculated based on the Italian national thermoelectric efficiency [49] while that of the cooling energy by considering a realistic value of the COP of a vapor compression chiller equal to 3 [50].

Details of the alternative investigated options for the different scenarios are summarised in Table 4.

Table 4. Characteristics of the different scenarios under investigation

	Conf.	Organic working fluid	Solar collector (m ²)	ΔT_h (°C)	ΔT_c (°C)	ΔT_m (°C)	E_e (kWh)	E_t (kWh)	E_c (kWh)	PEP (kWh)
Scenario 1	C1	R245fa	50	170-160	120-110	160-135	936.4	15061.1	5428.3	22576.8
	C2	R245fa	50	180-160	130-110	160-135	916	14713.9	4080.2	21191.5
	C3	R245fa	50	190-160	140-110	160-135	896.5	14102.8	3342.8	19947.9
Scenario 2	C1	R245fa	50	170-160	120-110	160-135	936.4	15061.1	5428.3	22576.8
	C4	R245fa	75	170-160	120-110	160-135	1631	24844.1	9052.1	37494.7
	C5	R245fa	100	170-160	120-110	160-135	2378	33738.9	12495.3	33017.2
Scenario 3	C1	R245fa	50	170-160	120-110	160-135	936.4	15061.1	5428.3	22576.8
	C6	Neopentane	50	170-160	120-110	160-135	1089.2	12740.6	4885.3	399007.1
	C7	R245ca	50	170-160	120-110	160-135	1235.3	12495.5	5113.5	402671.4

2.2.3 Impact assessment

In this study, the environmental and energy performances of the configurations under investigation are evaluated according to different indicators using IMPACT 2002+ model [51] in SimaPro 8.3.0, Intergovernmental Panel on Climate Change (IPCC) 2013 GWP 100a method [52] and cumulative energy demand method.

Twelve relevant midpoint indicators from IMPACT 2002+ model are identified for assessing the impact. On the contrary, the impact of non-renewable energy use, mineral extraction and global warming are excluded since they are taken into account by means of cumulative energy demand and IPCC methods. In addition, four endpoint indicators have been included for comparing the different configurations: (i) human health; (ii) ecosystem quality; (iii) climate change; and (iv) resources [53]. Eventually, two additional sustainability indicators, namely the energy payback time (EPBT) and the CO₂ emission factor, mainly used in LCA of energy systems [54–61], were also considered. More precisely, the EPBT is described as the ratio between the total primary energy consumption and the annual primary energy production. This indicator is calculated based on the cumulative energy demand which defines the total amount of the primary energy required in the entire life cycle of the trigeneration system. The CO₂ emission factor of trigeneration, instead, can be also counted as the carbon footprint during the entire life cycle divided by the total primary energy production.

3. Results and discussions

3.1 Environmental profile

The characterization is a mandatory step in environmental impact assessment. In this phase, using characterization factors, the set of inventory flows are quantitatively transformed to impact category indicators relevant to resources, ecosystems, and human health.

The categorized impact results associated with 1 kWh of primary energy production from the trigeneration system under configuration 1 (C1) are reported in Table 5. Figure 4, instead, illustrates the percent contribution of the different materials for the construction and operation of the plant to each impact category.

Table 5. Characterized impacts of the energy generated from trigeneration per 1 kWh of primary energy

Impact category	Units	Amount
Carcinogens	kg C ₂ H ₃ Cl eq	0.018
Non-carcinogens	kg C ₂ H ₃ Cl eq	0.064
Respiratory inorganics	kg PM _{2.5} eq	0.00057
Ionizing radiation	Bq C-14 eq	1.7
Ozone layer depletion	kg CFC-11 eq	3.28E-8
Respiratory organics	kg C ₂ H ₄ eq	0.00013
Aquatic ecotoxicity	kg TEG water	31.84
Terrestrial ecotoxicity	kg TEG soil	5.5
Terrestrial acid/nutri	kg SO ₂ eq	0.013
Land occupation	m ² org.arable	0.0032
Aquatic acidification	kg SO ₂ eq	0.0038
Aquatic eutrophication	kg PO ₄ P-lim eq	0.00016

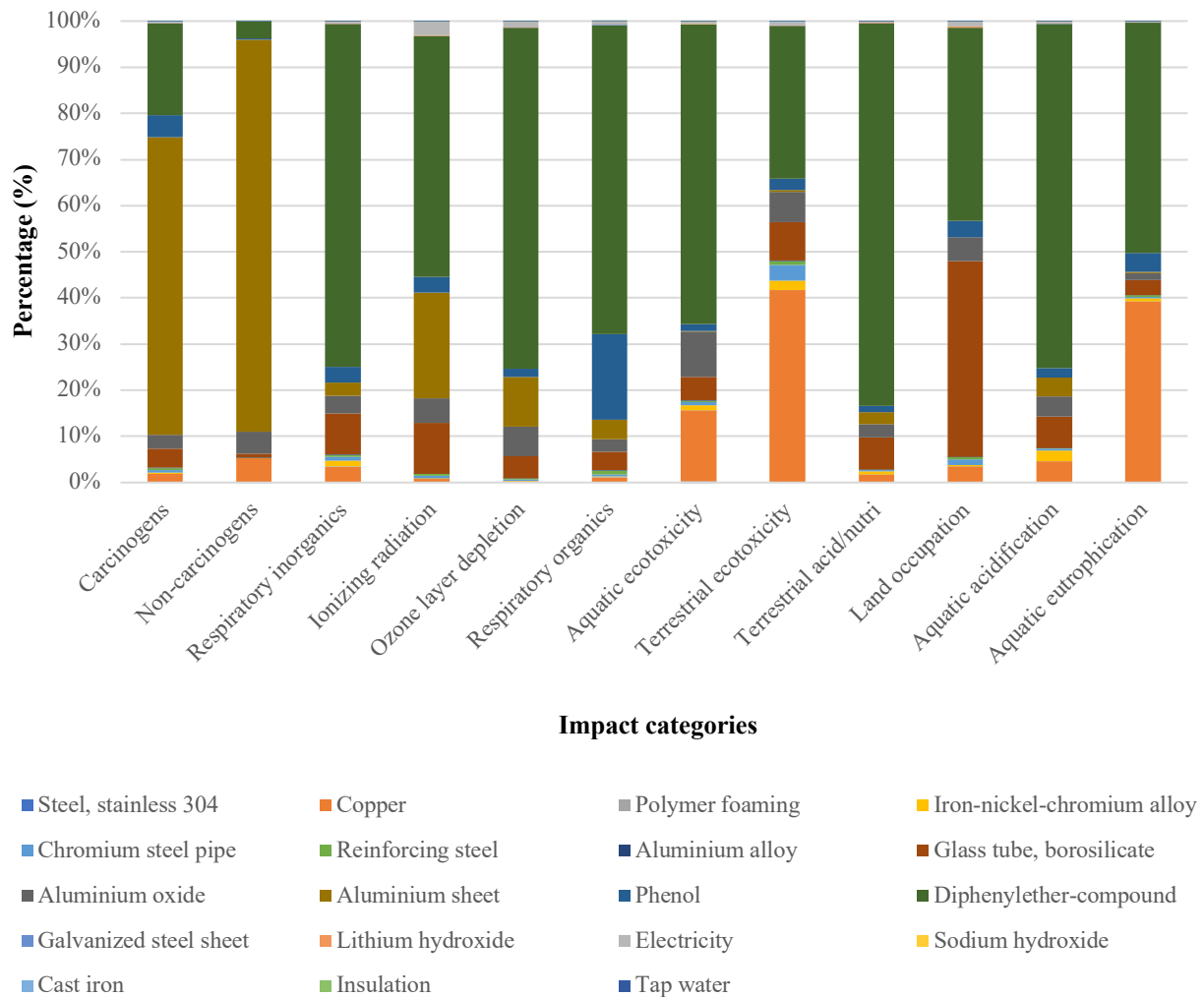


Figure 4. Environmental profile of 1 kWh of primary energy produced by the trigeneration system.

As clearly shown in Figure 4, the Diphenylether is the material that mostly impacts on the terrestrial acidification/nitrification (83%), the aquatic acidification (74%), the respiratory inorganics (74%), the ozone layer depletion (73%) and the respiratory organics (66%). Indeed, the production of Diphenylether releases toxic gases containing ammonia, nitrogen oxides and sulfur dioxide to the air. These emissions are responsible of acidification and they are extremely harmful to aquatic organisms. Therefore, the use of Diphenylether is an environmentally dangerous substance, and as a consequence its substitution can result in a significant reduction of many environmental impact indexes.

Instead, the production phase of the aluminum used in the solar CPC plant is the main responsible for non-carcinogens (85%) and carcinogens agents (64%) emissions which have dangerous effects on the human health. Since almost the entire amount of aluminum is used for the construction of the evacuated tubes solar collectors, it is evident that also this solar technology has a great impact on many environmental indicators.

On the contrary, copper used in ORC plant components contributes to about 40% of the terrestrial ecotoxicity and the aquatic eutrophication. This is because the production of copper releases

massive hazardous substances to air and soil, including aluminum, copper, and nickel, which affect the soil organisms [62].

3.2 Primary energy consumption and carbon footprint

The primary energy consumption and the carbon footprint are appealing impact categories in LCA studies of renewable technologies. Therefore, the contribution of the different materials to the carbon footprint and the non-renewable primary energy consumption has been assessed as reported in Figure 5. As shown in Figure 5, the construction and operating materials associated with the solar subsystem contribute to about 75% of the primary energy consumption of the whole trigeneration plant under investigation. The diathermic oil (Diphenylether and Phenol) and the materials of the evacuated tubes (glass, aluminum and aluminum oxide sheet) are the major contributors to the embedded primary energy consumption of the plant. In a paper, also Corona et al. [58] reported the high-energy requirements associated with the extraction and manufacturing of metal components (aluminum and steel) employed in the construction of a solar plant in Morocco.

As regards the CO₂ footprint during the entire life cycle of the integrated plant, the main contribution is due to the production phase of the Diphenylether mainly (57%) followed by the construction materials of the solar ORC. Therefore, the considered CPC solar plant has a significant impact also on the primary energy consumption and the carbon footprint profile of this trigeneration system. Also Burkhardt et al. [26] evaluated a concentrating solar power (CSP) system using four sustainability factors: life cycle greenhouse gas emissions, water consumption, cumulative energy demand and energy payback time. They specified that the largest contributors to the manufacturing-phase emissions are the solar collector assemblies.

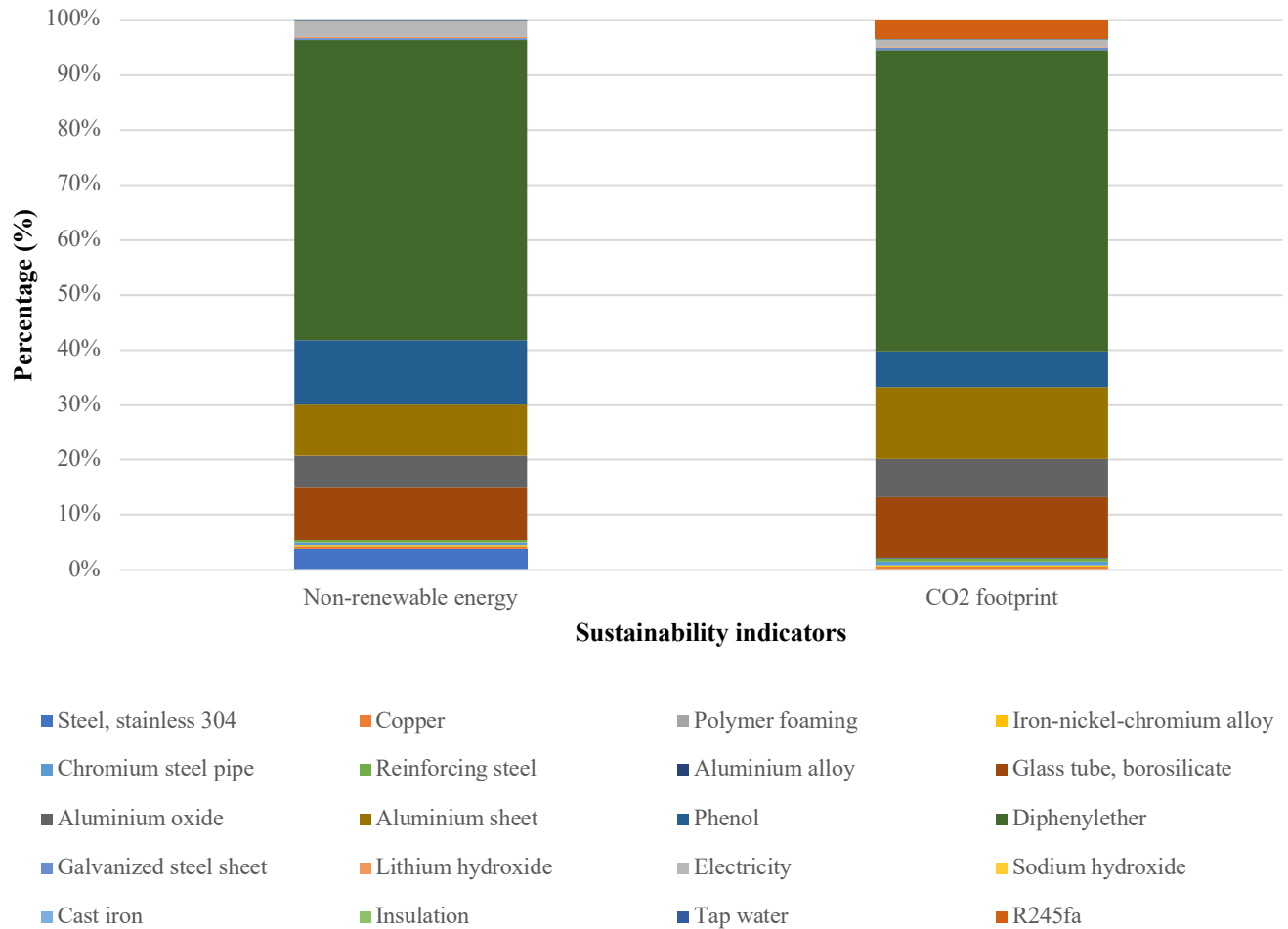


Figure 5. Process contribution to primary energy consumption and CO₂ emission per 1 kWh of primary energy production of the trigeneration system.

3.3 Comparison of scenarios

3.3.1 Endpoint indicators

Due to the great impact of some components of the plant on the overall environmental impact different scenarios have been investigated by varying some operating and design parameters. In case of Scenario 1, the working temperature ranges of the HTT have been varied and the damage in terms of endpoint results has been illustrated in Figure 6. The damage categories are reported by single score indicator in order to easily express the environmental loads of the integrated system. Simply, a higher score correlates to contributing more. The respective unit of single score, μPt , corresponds to the contribution to one European's share of the environmental impacts of the

entire life cycle of 1 kWh_{PEP} production in one year. The μPt expressed in one millionth (10^{-6}) of a point, allows to measure small impacts and to express these impacts more practically. With reference to Figure 6, configuration C3 has the largest impact in all the four damage categories, namely human health, ecosystem quality, climate change and resources because of its lower energy performance. Indeed, as reported in [15], the limited working temperature ranges of the HTT in case of configuration C1 allows to extend the operation of the trigeneration system throughout the year and increase the overall energy production of about 15% compared to configuration C3. Therefore, the overall energy efficiency of the system considerably affects also the related environmental performance.

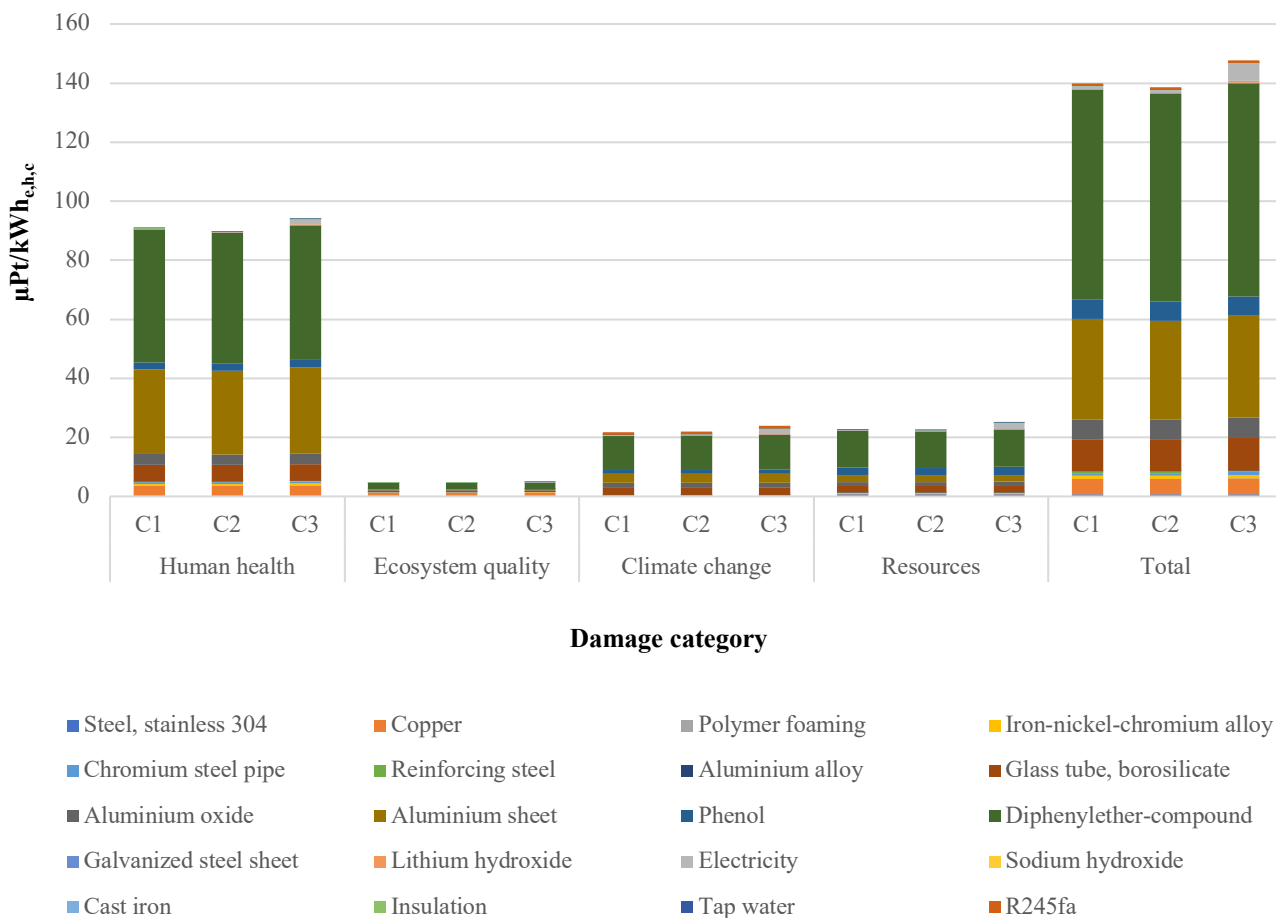


Figure 6. Damage assessment results in scenario 1 per 1 kWh of primary energy

In Scenario 2, instead, the size of the solar field has been varied due to the significant impact of the solar technology on the environmental indicators as previously shown. In particular, Figure 7 illustrates that configuration C5 characterized by the largest CPC collector area (100 m^2) has the lowest impacts per 1 kWh of primary energy production. Despite the amount of construction materials and diathermic oil increases with the size of the solar field, the higher energy production obtained by the trigenerative system more than compensate the damage derived. As a result, enlarging the solar plant has a significant benefit on the performance of the whole system and in case of C5 it leads to a 25% decrease of the total environmental impact. According to [63], where

a solar assisted absorption cooling system was applied, the substantial reductions in the environmental impacts were achieved by increasing the number of solar collectors followed by rising the solar fraction of the cooling system.

In addition, the results of both scenarios demonstrate that the system under investigation primarily affects the human health rather than the other damage categories. This is mainly due to the fact that in IMPACT 2002+ [53] the human health category comprises a collection of impacts such as ozone layer depletion and respiratory organics and inorganics which have an intensive burden on the environmental profile of system as described before.

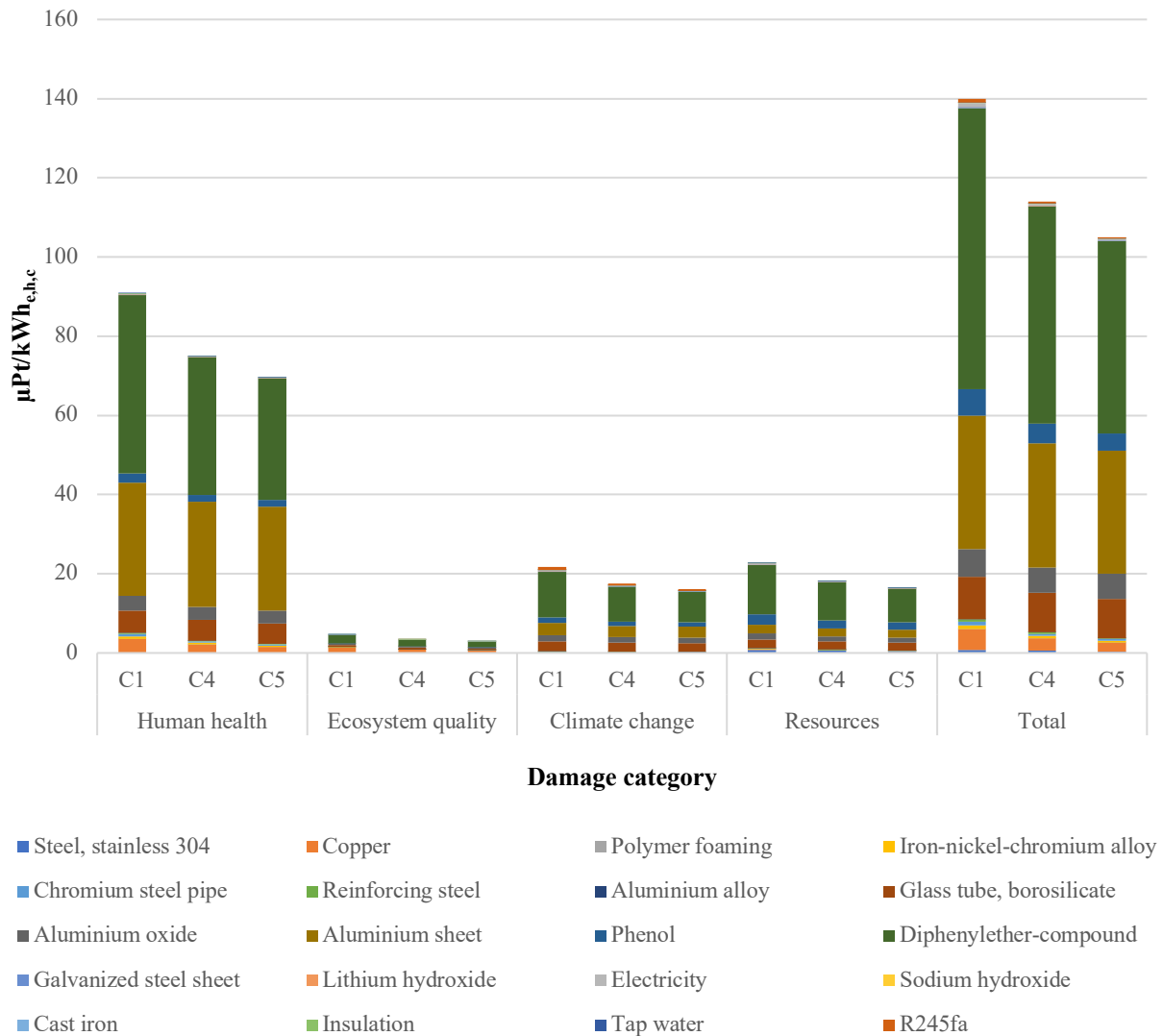
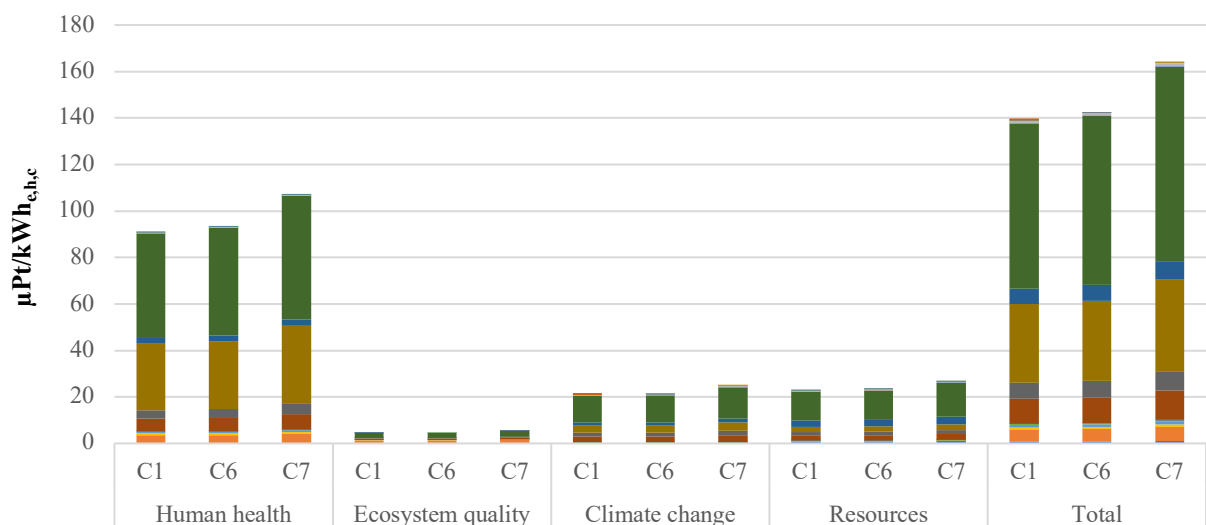


Figure 7. Damage assessment results in scenario 2 per 1 kWh of primary energy

Eventually, because of the fundamental role of the organic working fluid on the energy and environmental performance of the ORC system, in Scenario 3 the impact of two other different working fluids has been assessed. More precisely, Neopentane and R245ca have been considered additionally to R245fa since they represent the best compromise between good energy performance in case of low-temperature ORC systems and very low environmental impact in terms

of GWP. Despite the lower GWP of Neopentane and R245ca compared to R245fa, the analysis proved that the latter has the lower impact on the considered damage categories, as reported in Figure 8. Indeed, the use of Neopentane and R245ca brings to a significant decrease of the energy performance of the system and in particular of the thermal and cooling energy production. Therefore, the impacts related to the absorption chiller and the ORC unit intensify per fall in relevant energy outputs to these units, cooling and thermal energy, respectively. On the contrary, the higher energy performance of the ORC unit using R245fa as working fluid overcomes the poor environmental properties of the fluid. As a consequence, for the considered trigeneration system the use of R245fa results in lower environmental burdens compared to the use of Neopentane and R245ca.



Damage assessment

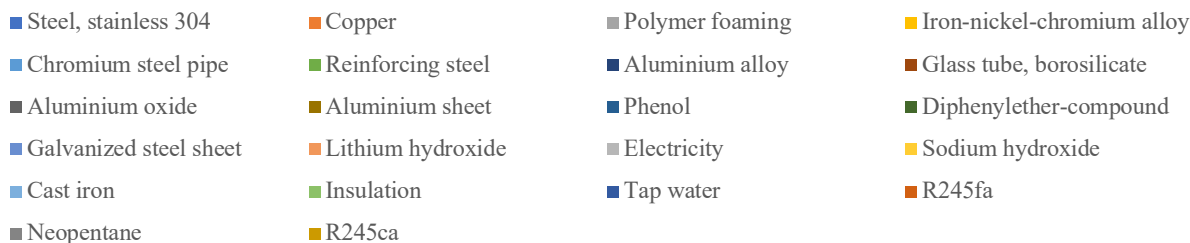


Figure 8. Damage assessment results in scenario 3 per 1 kWh of primary energy

3.3.2 Sustainability indicators

Eventually, the environmental performance of the integrated systems has been evaluated also with respect to the sustainability indicators previously mentioned. Table 6 reports a comparison of the energy payback time and the CO₂ emission factor among the different scenarios. It can be noticed

that configuration C5 has the shortest EPBT. More precisely, in this configuration the system achieves a EPBT of 14.8 years. The reason of such result lies in the highest annual energy production of the system that substantially compensates the intensive environmental burdens of the extraction of the raw materials.

With respect to the CO₂ emission factor, the results shown that the higher working temperature ranges at the HTT entail a higher CO₂ emission factor (configuration C3). On the contrary, the large scale of the solar field and the use of R245fa as working fluid (configuration C5) has the lowest CO₂ price which means that this configuration with specific operating conditions (namely lower working temperature ranges at the HTT) represent the best design solution of the trigenerative system under investigation.

Table 6. Sustainability indicators for the three scenarios

		Energy payback time (EPBT)	CO ₂ emission factor
		(year)	(kg CO ₂ per kWh of primary energy)
Scenario 1	C1	20.3	0.246
	C2	20.2	0.242
	C3	20.7	0.248
Scenario 2	C1	20.3	0.246
	C4	16.3	0.194
	C5	14.8	0.178
Scenario 3	C1	20.3	0.246
	C6	20.4	0.264
	C7	22.7	0.274

4 Conclusions

The environmental impacts of a small-size solarORC trigenerative system for residential applications have been assessed through a life cycle assessment and a sustainability analysis of the overall system. To the best of the authors' knowledge the application of a similar LCA analysis to small-scale CCHP solar-powered ORC plants has never been addressed in literature so far. Therefore, the present work, provides some useful insights to drive the design and construction choices of such energy systems considering both the energy and environmental point of views.

In particular, a sensitivity analysis of the system by varying some selected operating and design parameters has been performed and the following main findings have been obtained:

- the variation of the working temperature ranges of the HTT has an appreciable effect on the energy performance but a very low incidence on the sustainability indicators;
- despite the higher GWP, the use of R245fa allows to achieve better environmental benefits compared to R245ca (140 μ Pt/kWh_{PEP} with R245fa and 160 μ Pt/kWh_{PEP} with R245ca);

- for the considered trigeneration plant the use of R245fa and Neopentane is almost similar from the environmental point of view;
- the SM is the most effective parameter. Doubling the area of the solar field (from 50 m² to 100 m²) allows to reduce the energy payback time of the plant of almost 6 years (EPBT of configuration C5 equals to 14.8 years) and it entails a CO₂ emission factor of 0.178 kgCO₂/kWh_{PEP};
- an increase of the solar field from 50 m² to 100 m² brings to a reduction of the environmental impact from 140 μPt/kWh_{PEP} to 104 μPt/kWh_{PEP}.

In conclusion, a higher solar multiple makes the solar trigeneration system much more effective respect to the most important purposes of such a technology: a major energy efficiency and a lower environmental impact. Hence, a proper solar field area with respect to the ORC unit nominal capacity is the most affecting parameters on the energy and environmental performance of the system and needs to be carefully selected during the design of similar CCHP systems.

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