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COMPOST HEAT RECOVERY SYSTEMS: GLOBAL WARMING POTENTIAL IMPACT ESTIMATION AND COMPARISON THROUGH A LIFE CYCLE ASSESSMENT APPROACH

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ABSTRACT
Compost Heat Recovery Systems (CHRS) represent an innovative technology to provide domestic decentralized thermal energy, recovering the heat naturally produced during the aerobic biodegradation of waste biomass, coming from gardening/farming/forestry activities. CHRSs represent an alternative to centralized grid-connected power systems and are usually installed (combined with most traditional systems) to power underfloor heating systems (UHS) or domestic hot water systems (DHWS), lowering impacts and costs of thermal energy production. In this study, the Global Warming Potential (GWP) of CHRSs (measured as $kg_{CO2\text{-}eq}$/kWh) was investigated using life cycle assessment (LCA) approach, considering the whole life cycle of an average plant. CHRSs showed a negative Net value of GWP impact, equal to -0.268 $kg_{CO2\text{-}eq}$/kWh, as full balance of positive (0.062 $kg_{CO2\text{-}eq}$/kWh) and negative (-0.329 $kg_{CO2\text{-}eq}$/kWh) emissions. Negative emissions are related to avoided primary materials, replacement of natural gas used as traditional thermal energy production and replacement of mineral fertilizers. Considering only the positive emissions (0.062 $kg_{CO2\text{-}eq}$/kWh), CHRSs emerged to be in line with Solar Hot-Water Systems (0.061 $kg_{CO2\text{-}eq}$/kWh mean value) and slightly higher than Geothermal Systems (0.019 $kg_{CO2\text{-}eq}$/kWh mean value). Along with GWP impact, other midpoint and endpoint impact indicators were assessed and all showed a negative Net value: Particulate Matter PM (-2.36E-5 $kg_{PM2.5\text{-}eq}$/kWh), Fresh Water eutrophication FWE (-6.78E-06 $kg_{P\text{-}eq}$/kWh), Fresh Water ecotoxicity FWec (-2.10E-01 CTUe/kWh), Human Toxicity cancer effect HTc (-5.68E-09 CTUh/kWh), Human Toxicity non-cancer effect HTnc (-3.51E-09 CTUh/kWh) and Human Health HH (-5.22E-08 DALY/kWh). These results demonstrate that CHRS is extremely convenient considering both environmental and human health consequences.

1. INTRODUCTION

Aerobic biodegradation of biomass is an exothermic biological process able to release considerable heat, about 20,000 kJ/kg of organic matter degraded, rising the material temperature up to > 65° C (Di Maria et al., 2008; Themelis and Kim, 2002). At current level of technological and industrial development, this heat is usually dispersed into the environment. Previous studies already investigated the possibility of recovering such heat. Di Maria et al., (2008) reported the possibility of recovery from 4,000 kJ to 5,000 kJ per each kg of treated biowaste by the exploitation of a heat pump. In investigating 45 compost heat recovery systems (CHR) in 16 different areas, Smith & Aber (2017) reported the possibility of recovering about 7,000 kJ/ kg o dry matter by means of hot water for domestic purpose. First examples of CHR were documented in china sin 2000 years ago (Brown, 2014) but most recent concept of CHR were reported by Jean Pain with his book The Methods of Jean Pain: Another Kind of Garden wrote in 1972 (Pain and Pain, 1972). It basically consists of an iron welded mesh external structure, containing a compost pile usually made on woody biomass, inside which a heat exchanger is placed. CHRSs are traditionally insulated on the external part with straw bales and with a waterproof membrane placed at the bottom.

The biomass exploited inside CHRS plants is biologically decomposed through microbial respiration. When

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organic materials are metabolized by microorganisms, O_2 is consumed and CO_2 is liberated, while heat is metabolically generated. Numerous systems to recover this heat for domestic purposes have been tested over the years. The four main systems to extract heat from CHRS were summarized and schematically illustrated by Malesani et al., 2021. In the present study, the life cycle assessment was performed according to the traditional plant configuration pioneered by Jean Pain, that uses a conduction-based approach to recover heat with coiled PE pipes filled with an exchange fluid.

The involved biomass is usually lignocellulosic residual biomass that comes from gardening activities, pruning activities and landscape maintenance activities. Trees, grasses and harvest residues from food crops are the major sources of lignocellulosic biomass. According to Dahmen et al., (2019), every year are worldwide produced 4.6 billion tonnes of lignocellulosic biomass as agricultural residues, of which only 25% are used. CHRS systems improve the on-site reuse of this kind of biomass residue that otherwise should be transported, treated and disposed, with all the related costs and emissions.

At the end of the biodegradation process, the remaining material is compost material. This is an added value for CHRS, considering that compost is an excellent soil amendment to improve agricultural properties, since it increases both the soil organic carbon content and the soil nutrients content (Lord and Sakrabani, 2019). Moreover, it also improves the texture of the soil, allows to increase the water holding capacity of soils and sorb metals, having important impacts on physico-chemical properties of soils and enhancing plant growth and soil health in long terms (Mazumder et al., 2021).

Enhancing the on-site reuse of waste material and producing a still exploitable material to re-reuse on-site, while providing thermal energy, CHRS can be considered a technology that perfectly implements the principles of the circular economy. Normally defined as a new and sustainable model of production and consumption, circular economy involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible, extending their life cycle (Butti, 2020). In Figure 1, how CHRS puts into action the principles of circular economy, is schematically illustrated.

The transition to a circular model of economy is indeed relates to the ever-increasing problem of waste accumulation, along with the continuous exploitation of virgin resources, that are promoting the transition from the linear concept of "take-make-dispose" to a model designed in such a way that all the material and waste flows are reintegrated into a cycle (Tamburini et al., 2021).

The circular economy paradigm is based on the concept of the Life Cycle Thinking (LCT), as an approach that seeks to identify possible improvements to goods and services in the form of lower environmental impacts and reduced use of resource, assessing their whole life cycle from the extraction of raw materials to the end of their life (Lazarevic et al., 2012). Among the tools of LCT, the Life Cycle Assessment (LCA) has become a central instrument in environmental management to model, assess and evaluate the impact of a product or a process on ecosystems, natural resources of human health throughout its life cycle (VanderWilde and Newell, 2021). From a general point of view, LCA approach results able to account for the whole process "from cradle to grave" returning both environmental and health impacts by specific indicators (Di Maria et al., 2021).

Since CHRS are plants characterized by a low technology (low-tech), made of materials readily available in the place of construction and installation and they involve in their process the capture and storage of CO_2 with related benefits on the environment, the main objective of this study was to investigate CHRSs whole life cycle impacts on the environment. In LCA, all environmental impacts may be assessed. In the previous research (Malesani et al., 2021a), the authors investigated CHRSs overall costs considering the whole life cycle of the plant, while regarding the carbon dioxide emissions only the plant management

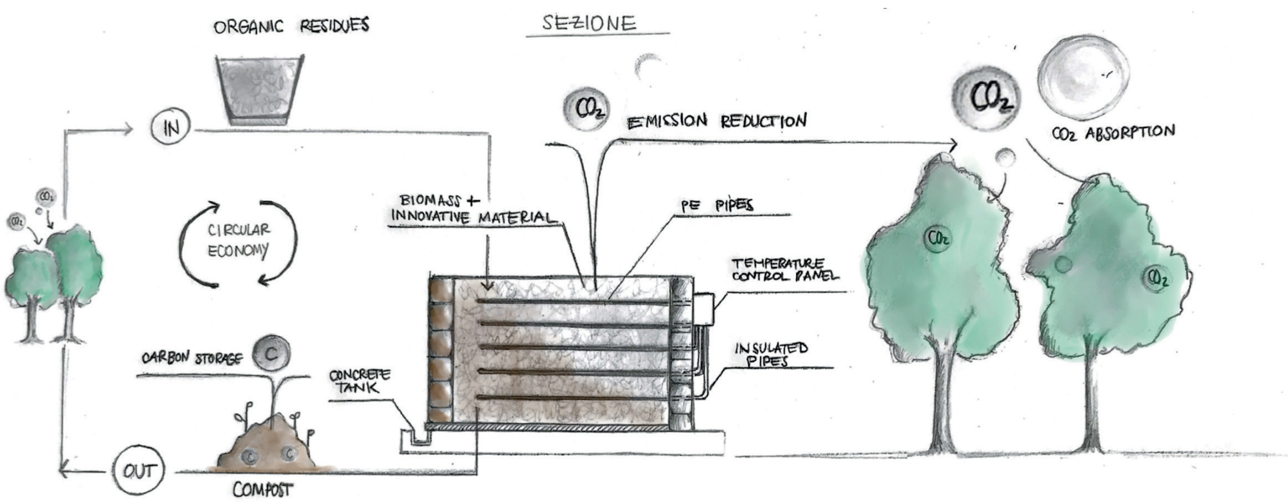

FIGURE 1: Schematic representation of the conceptual model of CHRS implementing the principles of circular economy, through the valorization of the residual biomass.

phase was considered. This further study allowed to estimate the overall emissions related to the whole life cycle through LCA approach of an average CHRS, since these are extremely interesting plants due not only to their very low $CO_{2\text{-eq}}$ emissions associated to every step of the life cycle, but also to their ability to store carbon in soil and avoid $CO_{2\text{-eq}}$ emissions thanks to the compost production and the biomass use. These multiple aspects of CHRSs are deeply interesting considering not only the global need to properly manage waste in a circular way, but also bearing in mind that the major challenge of this century is climate change and that to tackle this challenge, it is necessary to find measures to limit the temperature rise significantly reducing global CO_2 emissions and to reach carbon neutrality within the next 20 to 30 years (Rosenfeld et al., 2021).

Usually, LCA focuses on two key assessment variables: GHG emissions and the primary energy usage. This study focused on GHG emissions, that are mainly carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Other GHGs such as sulphur hexafluoride (SF6) and chlorofluorocarbons (CFCs) are not so relevant for energy systems, though SF6 is used to test oil and natural gas pipelines for leaks. Global Warming Potential (GWP) is used to express the contribution of different GHGs to global warming (Bird et al., 2006). In this study, several impact categories were assessed, but just the GWP impact category was deeply discussed and used to perform a comparison with the GWP values coming from literature about LCA studies performed on other technologies for sustainable thermal energy production, that are solar thermal panels and geothermal plants. The GWP data collected from literature, underwent a two-steps screening and were processed in order to have all the values expressed in $kg_{CO2\text{-eq}}$/kWh. A further statistical analysis was performed to better discuss the collected data.

2. MATERIALS AND METHODS

In this study, an evaluation of a traditional CHRS from a life cycle perspective was performed through an LCA study. The study was carried out with the final objective of comparing a CHRS to other sustainable plants for providing domestic thermal energy in terms of environmental impacts.

The evaluations and calculations were based on information deriving from real scale CHRS applications, designed with a traditional configuration.

2.1 CHRS description

The analysed CHRS essentially consists of a heap of raw woody biomass placed inside a cylindrical container system made of welded iron mesh. Since the role of the CHRS is to recover the heat produced from the composting process it is necessary to limit the heat dispersion, therefore the containing cylinder is surrounded by hay bales performing insulation. Water is needed by the system since its functioning is based on a biological process where an appropriate water content is essential to the microorganisms, so a waterproof bottom membrane placed at the bottom allows to collect the leachate produced, send it to a concrete well housing a recirculation pump and recirculate it from the top of the heap. The dimensions of traditional CHRS are usually in the range of 35 to 55 m^3, although this may vary from 25 to 170 m^3, according to Native Power association data (Native Power, 2019). In this study an average dimension of 55 m^3 was chosen to perform the calculations, meaning that the plant has the dimensions reported in Table 1. To ensure the adequate aeration (and oxygen required by microorganisms), perforated polyvinylchloride pipes are placed vertically inside the cylinder promoting airflow by means of a chimney effect (statically).

The generated heat is recovered by means of spirally arranged PE pipes fixed on wire mesh and placed at different heights inside the cylinder. The number of layers depends on the dimension of the plant. In this specific case, 5 layers of PE pipes were considered for a total amount of 500 meters of pipe.

Inside the PE pipes an exchange fluid flows, usually water. This fluid is then sent to an external puffer. The evaluation of the CHRS ends before the connection of the system to the building.

In Figure 2, a schematic representation on an average traditional CHRS is provided.

Since the biomass exploited inside a CHRS is biologically decomposed through microbial respiration, the plant works independently for a limited period. According to monitoring data of real scale plants performed by the current research group (Malesani et al., 2021b), this period usually lasts between 12 and 16 months. After that, the plant needs to undergo a maintenance service to be dismantled and quickly rebuilt with new biomass. During the dismantling of the plant the remaining biomass is extracted and valorized as compost.

This process can be done for several years reusing all the components of the plant; in this LCA study a 15-year CHRS lifetime was considered.

2.2 CHRS thermal power output

The thermal power generated over time by a CHRS can be evaluated from several available data of prototype plants and real scale domestic plants performing heat extraction from composting processes.

Over the past decades, many research papers about the heat generated from composting have been published. Table 2 reports some literature values of the thermal energy that can be recovered from composting processes involving woody biomass, together with further information collected from Native Power and Biomeiler organizations. Data were collected and processed to be homogenized.

TABLE 1: Characteristics of the considered CHRS.

Variable	Unit	Value
Diameter	m	5
Height	m	2.8
Circumference	m	15.7
Volume	m^3	55
PE layers	n	5
PE length	m	500

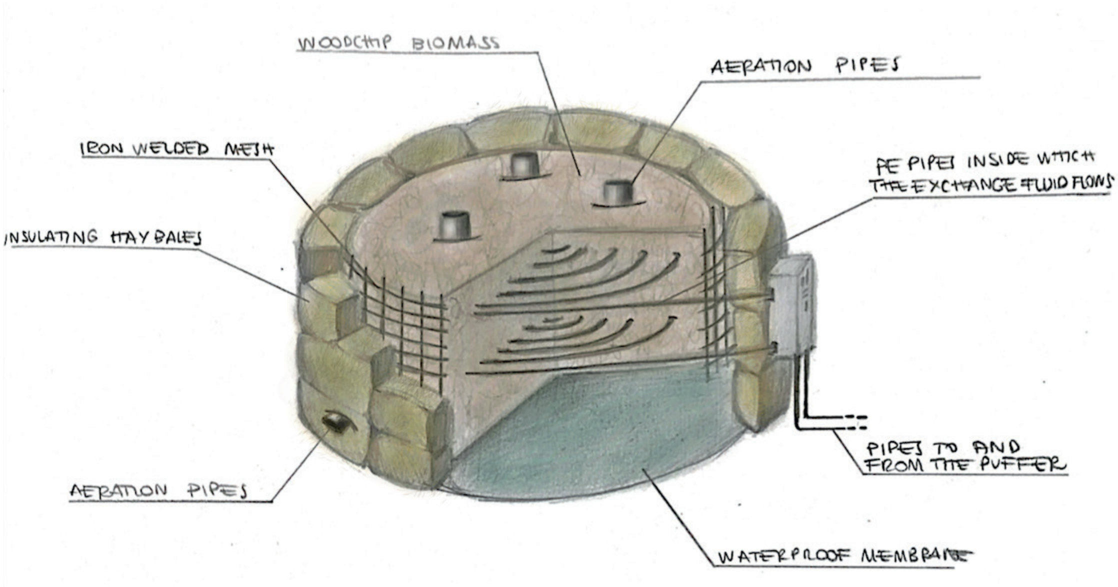

FIGURE 2: Graphic representation of a traditional CHRS.

The volumes of the plants that were considered, range from 0.09 m^3 (pilot scale) to 197 m^3 (real scale). Data about the thermal power output in kW per m^3 of biomass, range from 0.02 to 0.23 kW/m^3. Data can vary a lot depending on the volume of the plant and the duration of the biodegradation process, besides the kind of biomass used inside the plant.

Considering just the real scale plants (more than 30 m^3) that worked for about one year, the thermal power output of a CHRS ranges between 0.05 and 0.1 kW/m^3. This means that implementing a plant of 55 m^3, its power can range between 2.75 and 5.5 thermal kW.

Considering an average plant filled with woodchipped material, working 12 hours a day, with 0.1 kW/m^3 thermal power output, the total thermal energy that can be provided yearly is about 24,000 kWh.

2.3 Real scale CHRS data collection

In order to perform a LCA study, a list of materials and machineries used to install the plant and an estimation of electricity and operations needed to yearly maintain the plant, were necessary. All these data, when possible, were collected during the implementation, installation and operation of a real scale CHRS plant by the research group (Malesani et al., 2021a). Other data were retrieved from the databases used to perform the LCA study.

With regards to the materials involved in the installation of the plant and the need for use of specific equipment, means of transportation and electricity, they were assessed through the real scale plant design and construction and are reported in Supplementary materials A – CHRS list of materials. Machinery consumption has to be considered in the installation phase and in the yearly maintenance activities. Indeed, every year the biomass needs to be chipped before being put inside the plant, a wheel loader needs to be used to put the biomass inside the plant and a truck is necessary to transport the biomass from the place of its production till the plant installation site. Moreover, a recirculation pump for leachate works in the beginning phase, while a recirculation pump for exchange fluid recirculation works several hours a day for the whole lifetime of the plant. Trucks of 7 tons capacity were considered for the biomass transport and for material transport.

2.4 LCA study

The environmental impacts were assessed using an LCA approach according to the ISO 14040 (2006), ISO 14044 (2018) and the ILCD Handbook guidelines (EC, 2010,2012). All the calculations were performed using the SimaPro 9 software.

This study is a "cradle-to-grave" LCA, i.e., it mainly covers all relevant process steps from raw material production to the final waste treatment, recycling or disposal.

In a second step, the GWP results of the LCA were used to perform a comparison between CHRSs and other system to provide sustainable thermal energy. A literature review was performed in order to collect GWP data coming from several LCA conducted and published for two thermal energy generation technologies: solar thermal panels and geothermal plants. Having these LCA wide ranging results, due to technologies evaluated (i.e., differing system designs, commercial versus conceptual systems, system operating assumptions, technology improvements over time) and LCA methods and assumptions, a two-step rigorous screening evaluating the completeness, validity, and data quality of each study was necessary; nine studies were selected as representative, providing 44 data in kg_{CO2}/kWh that were used to perform the comparison.

2.4.1 Goal and system boundaries

The goal of the LCA study was to assess environmental impacts related to a CHRS, from the extraction of the raw materials, through its operative lifetime, to the final disposal or reuse of main components. First of all, the LCA study was performed on an average CHRS and the analysed system includes two main fluxes:

TABLE 2: Thermal power output from small scale composting processes; data coming from literature and elaborated by the research group.

Material	Energy recovered (Er)					Operative conditions				
	kW/m³	kWh/m³	MJ/m³	kWh/kg	MJ/kg	Operative time (h)	Moisture Content (%)	Bulk density (kg/m³)	Volume (m³)	References
Woodchips	0.05	406.1	1462	1.015	3.7	8640	70%	1000	55	(Native Power, 2019)
Woodchips	0.05	343.4	1236	0.859	3.1	6480	70%	1000	79	(Biomeiler, 2019)
Woodchips	0.16	112.5	405	0.113	0.4	720	70%	1000	16	(Zantedeschi, 2018)
Chipped brushwood	0.19	820.8	2955	1.492	5.4	4320	45%	550	75	(Pain and Pain, 1972)
Chipped brushwood	0.02	129.6	467	0.324	1.2	6480	NF	NF	197	(Schuchardt, 1984)***
Horse manure, sawdust, woodchips	0.14	83.0	299	0.175	0.6	600	60%	475**	0.9	(Chambers and Supervisor: Allen, 2009)
Bamboo	0.06	56.0	202	0.112	0.4	1008	46%	500	50	(Seki et al., 2014)
Woodchips	0.09	777.6	2799	1.637	5.9	8640	NF	475**	31	Brown, 2014***
Horse manure, woodchips, fresh grass	0.10	85.7	308	1.003	3.6*	864	58%	603	6.7	(Bajko et al., 2019)
Cow manure, grass, sawdust	0.23	70.8	255	0.149	0.5	312	58%	477	2.8	(Mwape et al., 2020)
Green waste	0.10	864.0	3110	1.819	6.5	8640	NF	475**	60	(Cuhls et al., 2020)***
Green waste	0.10	864.0	3110	1.819	6.5	8640	NF	475**	150	(Cuhls et al., 2020)***
Wood	0.06	560.5	1699	1.180	4.2	8760	60%	475**	134	(Kimman et al., 2019)

The factor used to convert MJ in kWh and vice-versa is 3.6 MJ/kWh. kWh/kg and MJ/kg are expressed in terms of kg of biomass. NF= Not Found.
** MJ/kgDM; ** assumed values of biomass density, when not available; ***cited after Zimmermann, 2020*

- On one side, the plant production starting from the extraction of raw materials for the production of main components of the plant, till their final reuse, recycling or disposal;
- On the other side, the production of raw organic biomass to use inside the plant, from the sowing of plant seeds, till the plant growing and harvesting to produce woodchipped biomass to feed the plant.

These components concur to the building and operation of the plant. A life span of 15 years was assumed. After each aerobic treatment cycle, the compost generated by the biomass has been assumed to be exploited on soil as organic fertilizer. Since it cannot be addressed to the specific CHRS all the energy consumption along with the efficiency in energy exploitation outside the CHRS facility were not include in the boundaries of the system (Figure 3), that include the production processes of the components that are necessary for the construction of the plant, the electricity and fuels necessary for its management, the energy consumption during the final composted material management. Direct emissions from the composting processes and indirect emissions due to the plant construction and management are considered and included. Given the multifunctionality of the system that involves energy and material transformation, system boundaries were expanded. Main backgrounds were represented by the activities of extraction of raw materials, manufacture of the main components of the plant, the activities of plants cultivation, their pruning and the wood chipping of the organic residues. Main foregrounds were represented by the CHRS plant operation, energy and organic fertilizer production.

This study was performed for research purpose, with the final objective of comparing the CHRS to other plants in terms of environmental impacts.

For taking into account the multi-functionality of the system that involves energetic and material transformations, the boundaries of the system were expanded (Figure 3).

2.4.2 Functional unit, reference flow and life cycle inventory analysis

The function of the system was the generation of 1 kWh of heat for civil heat needs. This was also assumed as reference flow. The reference flow is not able to significantly affect the backgrounds.

For the electricity consumed, the Italian energetic mix was considered referred to 2019, consisting of the following: natural gas 39%, oil 1%, coal 8.6%, other fuels 4%, hydroelectric 14.7%, geothermal 1.8%, wind 5.3%, photovoltaic 6.8%, bioenergy 5.8%, imports 13.2% (Terna, 2019).

Since the functional unit is considered to be constant the life cycle inventory (LCI) framework is attributional. Heat from Natural Gas fueled heat generator was considered replaced by the one recovered by the CHRS. Also, through the use of compost as soil fertilizer, the mineral fertilizers urea, phosphate P_2O_5 and potash K_2O were considered to be substituted. The amount of organic carbon stored in soil after compost application was considered to be the 15% of the compost total organic carbon, as average value between the values reported by Hermann et al., (2011) reporting that approximately 23% of the organic carbon remains in the soil as humus and Franz et al. (2009), according to whom about 8.2% of the organic carbon supplied with the compost would still be available in the soil over long periods (10-100 years).

Data obtained from measurements and calculations

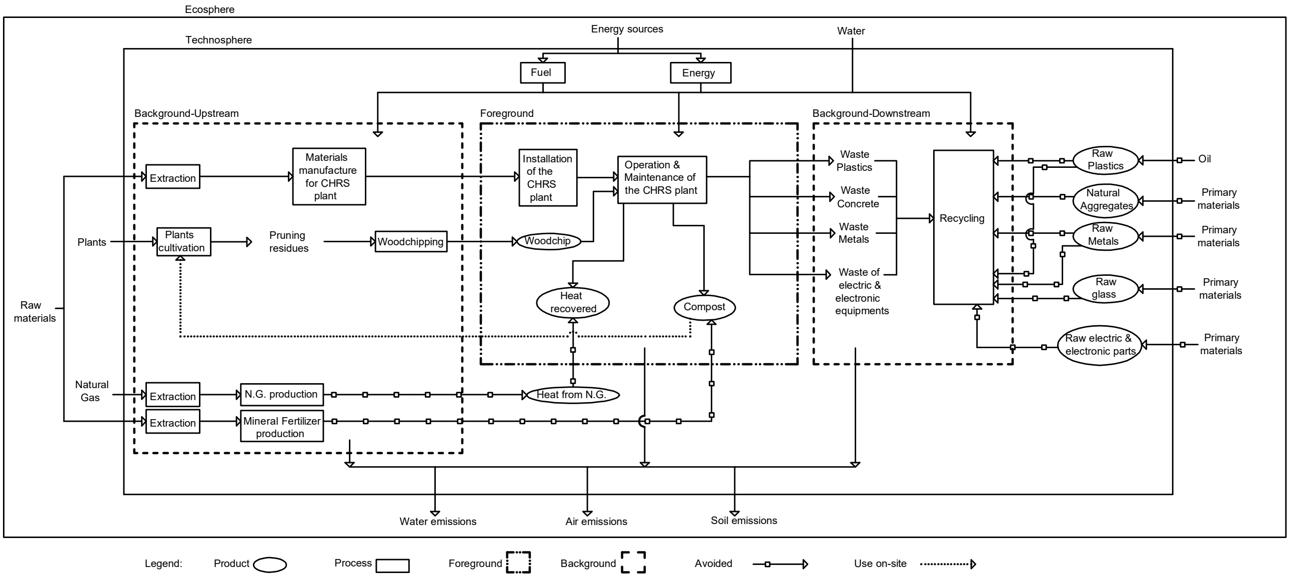

FIGURE 3: Boundaries of the considered system.

performed on the analyzed system, were used for adjusting the interested inventories retrieved from the Ecoinvent 3.7 database. All the materials involved in the installation of a real scale CHRS plant were considered based on the experience of the research team with the installation and monitoring of real scale plants.

2.4.3 Impact indicators and assessment method

Both midpoint and endpoint impact assessments methods were adopted. For the midpoint the ILCD 2010+ method (EC, 2012) was used considering the following impact indicators: Global Warming (GWP at 100 years) (kg_{CO2eq}); Particulate Matter (PM) ($kg_{PM2.5eq}$); Fresh Water Eutrophication (FWE) (kg_{Peq}); Fresh Water Ecotoxicity (FWec) (CTU_e – Comparative Toxic Unit for ecosystems); Human Toxicity, cancer effects (HT_c) (CTU_h – Comparative Toxic Unit for Human Health); Human Toxicity, non cancer effect (HT_{nc}) (CTU_h).

For the Human Health (HH) endpoint (DALY – Disability Adjusted Life Year), the IMPACT 2000+ (Jolliet et al., 2003) assessment method was used.

Since the goal of this study was mainly to assess, evaluate and describe the GWP impacts in terms of $kg_{CO2\text{-}eq}$/kWh, all the other calculated impact indicators are reported in Supplementary materials B – LCA impact indicators, including their graphic representations.

2.4.4 Uncertainty assessment

The margin of error related to the LCA results obtained during the present study, was assessed through a simplified standard procedure based on a pedigree matrix that takes pattern from a work published by Weidema & Wesnæs (1996) and based on the use of basic uncertainty factors (U_b) reported by Frischknecht et al. (2007). The basic uncertainty factors come from expert judgements.

Data sources were assessed according to the following characteristics: reliability, completeness, temporal correlation, geographical correlation and further technological correlation. Each characteristic is divided into five quality levels with a score between 1 and 5, that is assigned to each indicator of the pedigree matrix according to the quality of the available data. On the basis of the assigned score, each indicator corresponds to a given uncertainty factor: U_1=uncertainty factor of reliability, U_2=uncertainty factor of completeness, U_3=uncertainty factor of temporal correlation, U_4=uncertainty factor of geographical correlation, U_5=uncertainty factor of other technological correlation (Di Maria and Micale, 2014). These factors are also based on expert judgements and are reported by Frischknecht et al., (2007).

Once all these values were determined, the square of the geometric standard deviation was then calculated, with a 95% confidence interval, according to Equation 1:

$$SD_{g95} = \sigma_g^2 = exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_b)]^2}} \quad (1)$$

2.5 Literature data collection and screening approach

Positive emissions of equivalent CO_2 related to the whole life cycle of the CHRS (GWP impact) were finally used to perform a comparison with literature data collected from several LCA studies conducted on other sustainable thermal energy production system: solar thermal panels and geothermal plants.

To collect data from LCA studies, a comprehensive search of the literature was performed. Studies collected were reviewed and screened in two steps.

The studies that passed the first screening step should:

- Be written in English
- Be published after 2010
- Be published as: journal article, conference proceeding, book or book chapter
- Cover thermal energy technologies from solar or geothermal sources

- Report qualitative results from an LCA or review results from multiple LCAs
  The second screen consisted of three main criteria:

- Quality: the study had to employ a currently accepted LCA methodology (e.g., following ISO 14040 series standards [ISO 2006]).
- Transparency: the study must report the method transparently providing a description of the system and reporting impacts qualitatively.
- Relevance: the study must evaluate a modern technology, relevant to current or near future.

The studies that passed the two screening steps provided 44 estimates of life cycle CO_2 emissions for the aforementioned technologies and were included in this analysis. Multiple emission estimates from a single reference were considered when different technologies were analysed. Indeed, several references that passed the two screens, provided more than one estimate value, based on either alternate scenario or alternate technologies, e.g., Martinopoulos et al. (2013) performed LCA on a variety of typical Domestic Solar Hot Water System (DSHWS) providing 28 data, Comodi et al. (2016) performed LCA on two different DSHWS, glazed and unglazed, A. S. Pratiwi & Trutnevyte (2021) quantified the life cycle impacts of 6 heating and cooling configurations with geothermal wells providing 6 data and others.

The total amount of 44 emission data drawn from 9 reference, then underwent a processing process necessary to express all of them in kg_{CO2}/kWh. To be considered, studies were required to either directly report life cycle emissions in kg_{CO2} per functional unit or to provide sufficient information to calculate it without using exogenous assumptions. Even rigorous studies did not report emissions in kg per functional unit. To limit errors, the results had to be reported numerically, not only graphically, as happens in many LCA studies.

Duplicate estimates from one study quoting another or from the same author group publishing the same estimate multiple times were not included.

Finally, key parameters values had to be reported to be considered for comparison. The required parameters were:

- Operative lifetime
- Thermal load (in MJ/y or kWh/y). When it was reported in MJ/y, it was converted using a conversion factor of 3.6 MJ/kWh
- Functional unit

Data retrieved from literature were processed and elaborated to achieve uniformity of the unit of measure into kg_{CO2}/kWh. Specifically, Martinopoulos et al. (2013) reported the load covered by Domestic Solar Hot Water System (DSHWS) in MJ/y and the environmental impacts of DSHWS divided into CO_2, CH_4 and N_2O for a total amount of kg of CO_2, kg of CH_4 and kg of N_2O emitted in 15 years. They also reported the kg of CO, NMVOC, NO_2 and SO_2 but they were not considered since they are climate-altering gases with an indirect effect on climate, not directly contributing to Global Warming. So, first the load covered by DSHWS was converted into kWh/y with a conversion factor of 3.6 MJ/kWh, and then a total amount of kg of equivalent CO_2 emitted in 15 years were calculated converting CH_4 and N_2O emissions into emissions of equivalent CO_2 considering the 100-year global warming potentials (GWP100) equal to 28 for CH_4 and to 265 for N_2O. Having the total thermal load covered by DSHWS in 15 years expressed in kWh and the total emissions of $CO_{2\text{-eq}}$ in 15 years expressed in $kg_{CO2\text{-eq}}$, the values were expressed in $kg_{CO2\text{-eq}}$/kWh. The same procedure was applied for data reported by Comodi et al. (2016); the thermal load expressed in MJ/y, was converted into kWh/y with 3.6 MJ/kWh conversion factor and, regarding the global warming potential of DSHWSs already reported in $kg_{CO2\text{-eq}}$, only emissions of CO_2, CH_4 and N_2O were considered. Having the total thermal load expressed in kWh and the total emissions expressed in $kg_{CO2\text{-eq}}$, the values were expressed in $kg_{CO2\text{-eq}}$/kWh. Albertí et al. (2019) directly reported the values of the Global Warming impact in kg_{CO2}. All of the other cited studies (Frick et al., 2010; Karlsdottir et al., 2014; Lacirignola and Blanc, 2013; Pratiwi et al., 2018; Pratiwi and Trutnevyte, 2020, 2021) reported the values of the Global Warming impact in $kg_{CO2\text{-eq}}$/MWh so the values were just expressed in $kg_{CO2\text{-eq}}$/kWh.

2.6 Statistical assessment and comparison

Data collected according to the approach described in the previous paragraph, were statistically analysed and graphically represented using Microsoft Excel. The descriptive statistic was performed (calculating mean, median, minimum, maximum, first and third quartile and interquartile range) and the resulting descriptive statistics were further summarized graphically through boxplots. Boxplot representations are among the most widely used exploratory data analysis (EDA) tools in statistical practice and they allow to quickly visualize the degree of dispersion of the data and they intuitively reflect outliers. Since the adoption of real-life data set, the Boxplots methods, quartiles and interquartile range are chosen as the basis of judgment, which will not be affected by outliers (Li et al., 2016).

The results of the statistical analysis were used to evaluate the variability and the central tendency of the dataset collected from literature, to determine how reliable the comparison it is.

3. RESULTS AND DISCUSSION

GWP impact values in $kg_{CO2\text{-eq}}$/kWh were assessed and used to perform a comparison with other environmental damages data found in literature about other domestic heating systems from renewable sources.

3.1 Environmental effects

The LCA indicated that all the environmental impacts related to the implementation of a CHRSs due to direct and indirect emissions (positive emissions) are lower respect to the benefits due to the avoided primary materials, the replacement of natural gas used as traditional thermal energy production and the replacement of mineral fertilizers (negative emissions). Indeed, from all the impact categories considered emerged a final net negative value, since positive emissions are lower than negative ones. This can be clearly seen from the graphs reported in Supplementary materials B – LCA results.

In Figure 4, the GWP impact for each step of the life cycle of CHRS in terms of $kg_{CO2\text{-}eq}$/kWh is shown. As can be seen, the negative net value indicates the benefits related to CHRS implementation.

Main contribution to GWP impact were by direct and indirect emissions from the plant management phase (operative lifetime of the plant), with a total amount of positive emissions of 0.056 kg_{CO2}-eq/kWh, mainly due to the gasoil use for:

- the wheel loader use, for plant filling (37%)
- the woodchip material transport (33%)
- the wood-chipping machine use (29%)

The percentages are referred to the total amount of positive emissions related only to the plant management phase and all the detailed positive and negative emissions with related percentages can be found in supplementary materials.

Emissions from the materials manufacture resulted quite limited too, with a total amount of 0.005 $kg_{CO2\text{-}eq}$/kWh, mainly related to the production of the:

- polyethylene pipes inside which the exchange fluid flows (29%)
- stainless steel welded mesh for the external structure of the plant (25%)
- pumps for recirculating water inside the PE pipes and leachate from the bottom of the plant to the top of it (12% and 12%).

The contribution of the end-of-life stage was practically negligible (0.0002 $kg_{CO2\text{-}eq}$/kWh) since every component of the CHRS is reused or recycled except for the waterproof membrane that is sent to an incineration system with energy recovery. The negative value related to avoided primary materials (avoided thanks to material reuse ore recycle) is equal to -0.006 $kg_{CO2\text{-}eq}$/kWh.

The main contribution to the avoided emissions, is related to the avoided heat production (-0.275 $kg_{CO2\text{-}eq}$/kWh). To evaluate it, it was considered to substitute with a CHRS, a traditional gas heating system. The avoided emissions related to the avoided mineral fertilizer are equal to -0.048 $kg_{CO2\text{-}eq}$/kWh, and it is mainly due to the carbon stored in soil in 15 years of CHRS use (88%).

The combination of the benefits achieved avoiding the use of mineral fertilizers, avoiding the heat production from natural gas and avoiding the primary materials use thanks to material recycle and reuse, leaded to a negative net value of -0.268 $kg_{CO2\text{-}eq}$/kWh.

The numerical values of the GWP impact for each stage are reported in the graphical representation in Figure 4.

From the outputs of the whole LCA, observing all the considered impact categories (reported in Supplementary materials B – LCA results), emerged that CHRS implementation is clearly beneficial in terms of equivalent carbon dioxide emissions, particulate matter emissions, human health, human toxicity, fresh water ecotoxicity and fresh water eutrophication. The findings suggest indeed that, on average, the impact on environment and human health of both direct and indirect emissions from the use of CHRS with heat recovery and compost production, are definitely lower than those due to the production of the same amount of mineral fertilizer, the same amount of heat with natural gas and virgin materials replaced.

For further comparison with other technologies, just the positive emissions were considered, equal to 0.062 $kg_{CO2\text{-}eq}$/kWh.

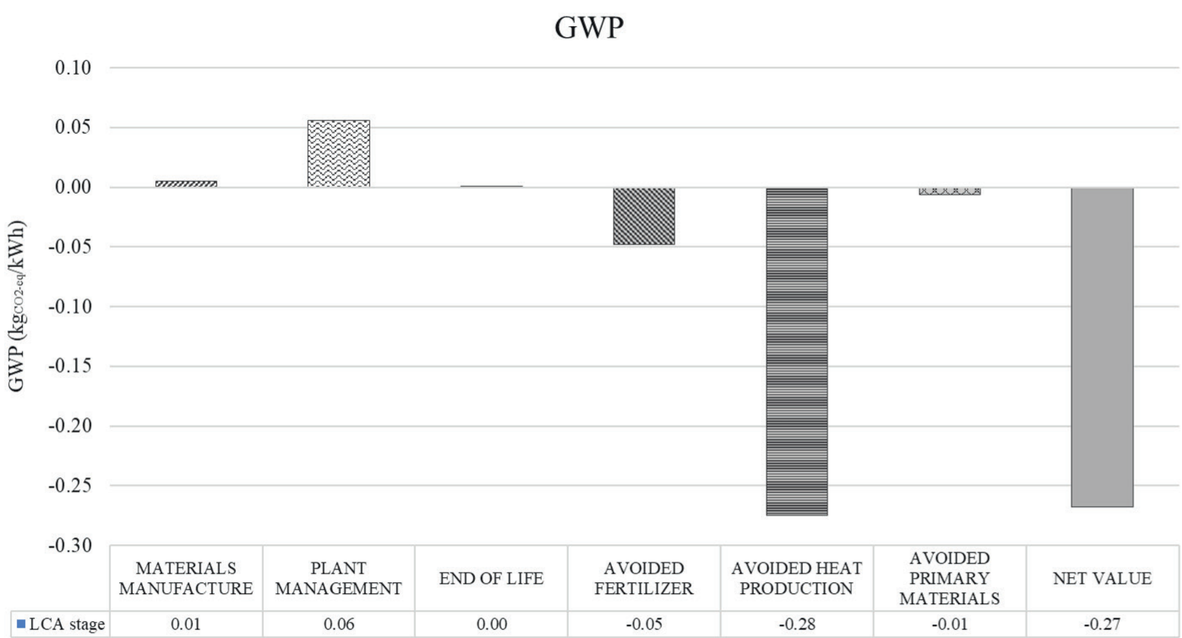

FIGURE 4: Schematic representation of the conceptual model of CHRS implementing the principles of circular economy, through the valorization of the residual biomass.

3.2 Uncertainty assessment

Only the main emissions contributing to the GWP impact category were considered for the uncertainty evaluation. Due to the independency assumed for the background from the system foreground, only direct emissions generated by the processes were considered. Indirect emissions and emissions not influenced by the main process of plant functioning, were not considered (i.e. Materials manufacture phase). Moreover, due to the marginal effect that End of life phase has on the overall GWP impact of the CHRS (contributing for 0.4% to the total emissions), the uncertainty analysis of the related database was omitted.

The CHRS plant was simulated based on the expertise developed by the research group during a real scale plant construction and monitoring with respect to the year 2018. On field data were collected during one-year plant operation and, when not fully available, data were retrieved from literature (i.e plant thermal power output). Woodchip machine use, recirculating pumps functioning, and wheel loader use are real data so high-quality data corresponding to low scores. Regarding the material transport, real data were not available, so an average distance of 20 km was assumed because CHRSs are plant meant to be implemented close to the place where residual biomass is produced. Data were collected from one plant that operated for one year, so the data from the remaining years of operation were estimated on the base of the first year of operation. The LCA was performed considering the real geographical area under study and the electricity mix considered for electricity consumption, is the Italian energetic mix referred to year 2019. For all these considerations, the values associated to the quality indicators of the pedigree matrix are 2, 4, 2,1 and 1 respectively.

On the basis of the data reported in Frischknecht et al. (2007) for Uncertainty factors and on the basis of the Eq (1), the variance was evaluated. Uncertainty factors scores and values assigned are showed in Table 3, together with the final variance value equal to 1.13.

Results show that CO_2 emission s_g^2 reflects substantially the basic uncertainty factor U_b, indicating that the uncertainty contribution introduced by the pedigree matrix is not relevant. In fact, s_g^2 equal to 1.13 emerged to be just 7,5% higher than U_b, equal to 1.05.

The higher Uncertainty factor is the second one, related to Completeness of the data, since the plant was monitored for a shorter period of time respect to the operative lifetime considered for the LCA.

The main reason, contributing to the resulting variance, is the fact that data comes from real scale plant designed, built and monitored by the research group, hence uncertainty factors related to geographical correlation and further technological correlation are the lowest ones.

4. COMPARISON WITH OTHER TECHNOLOGIES

Positive direct and indirect emissions of equivalent CO_2 related to the whole life cycle of the CHRS (GWP impact) were used to perform a comparison with literature data collected from several LCA studies conducted on solar thermal panels and geothermal plants. Negative emissions (avoided emissions) were not considered in this comparison, since data collected from literature only concerned the kg of $CO_{2\text{-eq}}$ produced during the life cycle of the plants.

4.1 Data collection and statistical assessment

Collected values were expressed in $kg_{CO2\text{-eq}}$/kWh in order to be foreseeably comparable to the values obtained from the current LCA performed on CHRSs. The values found in literature that passed the screening approach and were considered for statistical assessment and comparison, are resumed in Supplementary materials D – literature data collection. A total amount of 44 values were considered, 31 related to SHWS and 13 related to GHS.

When the values were not expressed in $kg_{CO2\text{-eq}}$/kWh, they were processed or converted with adequate conversion factors. Processed values are marked in the table reported in supplementary materials.

A statistical assessment of variability and central tendency of the processed dataset was performed. Central tendency is reported using both the medians and arithmetic means od the datasets. The variability of the datasets is also described using multiple parameters, including the range (difference between maximum and minimum values) and the interquartile range (IQR) bounded by the 25th and the 75th percentile values. Figure 5 displays box plots for the life cycle carbon dioxide emission estimates of the two technologies considered in the present study and numerical results are provided in Supplementary materials E – statistical analysis.

From the Boxplot statistical representation (Figure 5), it emerges that the datasets about Solar Hot Water System (SHWS) and Geothermal Heating Systems (GHS) in $kg_{CO2\text{-eq}}$/kWh have a low variability, especially for SHWS, meaning that data are well consistent and do not vary a lot from the mean value equal to 0.06 $kg_{CO2\text{-eq}}$/kWh It also emerges from the interquartile (IQ) ranges, equal to 0.006 for SHWS. Moreover, on one side, as can be seen from the graph, SHWS data follow a quite normal distribution where

TABLE 3: Scores and values assigned to uncertainty factors and resulting variance for GWP impact category.

	Reliability	Completeness	Temporal correlation	Geographical correlation	Further technological correlation	Basic uncertainty factor CO_2	Square of the standard deviation
Uncertainty factors	U_1	U_2	U_3	U_4	U_5	U_b	
Scores	2	3	2	1	1		
Values	1.05	1.10	1.03	1	1	1.05	1.13

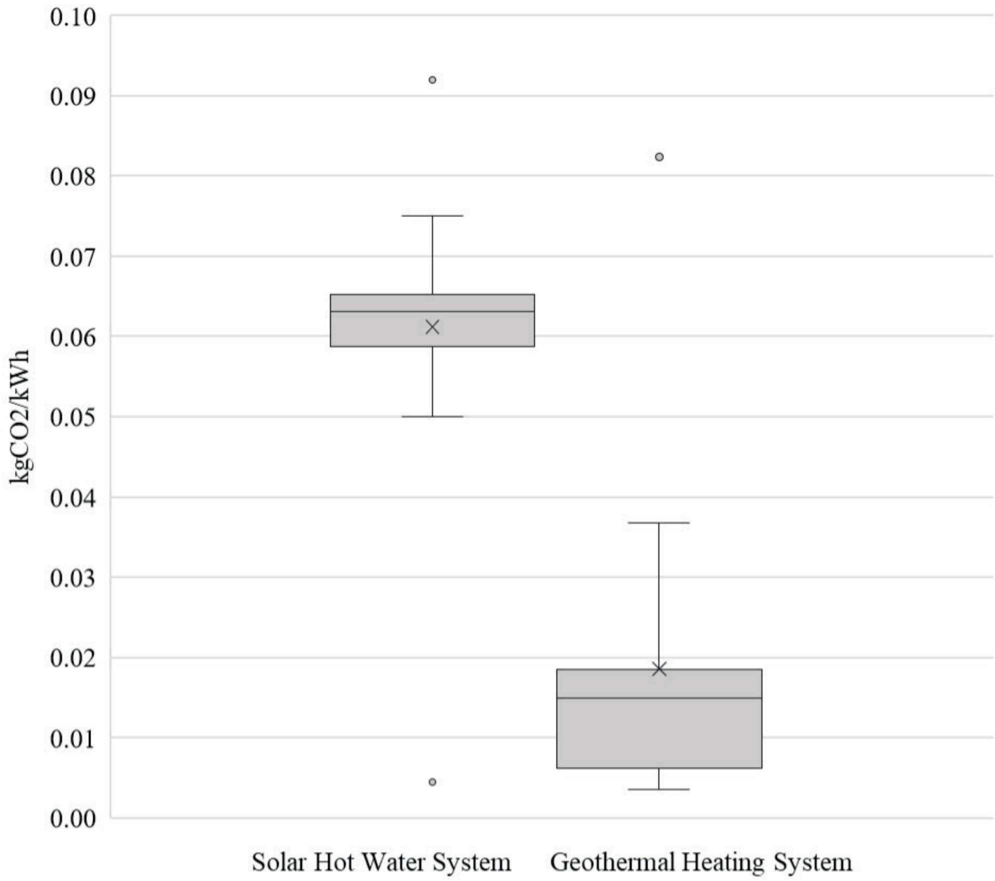

FIGURE 5: Box plot of the GWP impact in kg_{CO2-eq}/kWh for Solar Hot Water Systems and for Geothermal Heating System (literature data). The line within the box shows the median value, the box denotes the range of 50% of data, X stands for the average value and dots stand for outliers.

mean and median values are almost equal (0.061 and 0.063 kg_{CO2-eq}/kWh respectively), well describing the behaviour of the dataset. On the other side, GHS distribution emerges to be asymmetric, rightly skewed, with a median value equal to 0.015 kg_{CO2-eq}/kWh lower than the mean value equal to 0.019 kg_{CO2-eq}/kWh.

4.2 Data comparison and discussion

Just considering the positive emissions assessed through the LCA study equal to 0.062 kg_{CO2-eq}/kWh, CHRSs is in line with the literature data collected for SHWS (mean value 0.061 kg_{CO2-eq}/kWh), while it is slightly higher than the values collected for GHS (mean value 0.019 kg_{CO2-eq}/kWh).

Finally, it is worth noting that CHRSs compared with traditional systems to provide domestic heating is way more sustainable in terms of kg_{CO2-eq}/kWh. Indeed, from literature some data about the use of Electricity and Natural Gas Systems (NGS) for domestic heating were also collected: from Martinopolous et al. emerged a value of 1.41 kg_{CO2-eq}/kWh if the thermal load is entirely covered by electricity, using country specific data for electricity production in Greece (Martinopoulos et al., 2013) and Pratiwi reported a value of Bayer et al. of 1.18 kg_{CO2-eq}/kWh as electricity mix average carbon emission in Poland (Bayer et al., 2013; Pratiwi and Trutnevyte, 2020). Moreover, Albertì et al. reported 0.264 kg_{CO2-eq}/kWh for domestic hot water production from NGS (Albertí et al., 2019).

5. CONCLUSIONS

CHRS is in a position to compete on the market with both traditional and green technologies to provide sustainable domestic heating. Malesani et al. (2021) reported a comparison between different scenarios involving CHRS, pellet combustor, natural gas condensing boiler, solar thermal panels and geothermal plant to heat a farmhouse located in northern Italy and demonstrated that the implementation of CHRS allow to decrease the cost in €/kWh provided considering not only the operative phase, but also the capital costs (design, construction, installation) and the dismantling costs.

This study represents a further research about the emissions related to the full life cycle of CHRS by means of a LCA study, to evaluate the feasibility of installing CHRS as alternative to other heating system with advantages in both economic and environmental viewpoints. The CHRS was analyzed as a system to produce heat in order to be comparable with other heating system, considering the kWh of thermal energy produced by the system.

Considering both positive and negative emissions related to all the life cycle stages, CHRSs present a negative Net value of GWP indicator emissions equal to -0.268 kg_{CO2-eq}/kWh.

Compared with Solar Hot Water Systems and Geothermal Heating Systems considering only the positive emissions, CHRSs emissions of CO_{2-eq} emerged to be in line with SHWS and to have slightly higher emissions than GHS. Considering the traditional technologies for domestic heating (Electricity and Natural Gas Systems), CHRSs appear to be far more environmentally sustainable in terms of emissions.

To conclude, the utilization of renewable technologies as alternatives to conventional heating systems generally results in low emissions of greenhouse gases. GWP impact values ranging from 0.004 to 0.092 kg_{CO2-eq}/kWh were found for SHWS and ranging from 0.004 to 0.082 kg_{CO2-eq}/kWh were found for GHS though a literature review and data collection process. A positive value equal to 0.062 kg_{CO2-eq}/kWh and a negative value equal to -0.329 kg_{CO2-eq}/kWh were calculated through LCA for an average CHRS. Positive values are especially related to the use of specific machineries for yearly plant maintenance, while the negative value mainly represents the emissions avoided thanks to the use of a CHRS respect to the use of a conventional heating system and thanks to the use of compost as fertilizer respect to the use of conventional mineral fertilizers. The negative Net value underlines the highly beneficial aspects related to the implementation of a CHRS considering its overall life cycle emissions.

A further possible evaluation of the system could consider the kWh of thermal energy available for a domestic utilization and has to be implemented to specific cases considering detailed aspects of a plant, among which: the distance of the plant from the final user, the specific type of heat exchanger, the temperature levels required by the users' building and so on.

This first step of environmental impacts and advantages related to the implementation of a CHRS allowed to demonstrate that it is worth investigating in more depth and detail the real-scale implementation and utilization of CHRS, especially comparing it with other system to provide domestic thermal energy, since it emerged of having great potential to enter the market of sustainable heating production with very low costs and low environmental impacts.

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