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Compost Heat Recovery Systems: An alternative to produce renewable heat and promoting ecosystem services

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ABSTRACT

Aerobic biodegradation of biomass can release considerable heat, reaching temperatures of up to 65 °C. This heat can be recovered and used for domestic purposes through the implementation of Compost Heat Recovery System (CHRS). In this study, data were collected from a full-scale CHRS, fed with tree-pruning residues, installed in a farmhouse located in Northern Italy. The CHRS (2.75 kW average heating power) worked in conjunction with a pellet combustor for one year.

Energy and carbon balances were analyzed and compared (over a 15-year life-time) with combinations of alternative heating systems (both traditional and green ones). The real case study provided a heat supply at a competitive cost (0.087 € kWh^{-1}). A scenario with two CHRSs would further decrease costs (0.074 € kWh^{-1}). In terms of the carbon balance, a CHRS can save up to 0.252 $kg_{CO2\text{-eq}}$ kWh^{-1} of energy produced, compared to a fossil-fuel alternative (natural-gas), while promoting carbon storage for around 0.05 $kg_{CO2\text{-eq}}$ kWh^{-1} in agricultural soils by compost amendment. Over a 15-year period, each module can potentially substitute fossil-derived heat for around 264 $MgCO_{2\text{-eq}}$, while increasing soil carbon pool by around 20 $Mg_{CO2\text{-eq}}$, as C-stock calculated on a medium-term scenario (100-years).

CHRSs have great potential to furnish renewable heat at competitive prices, while providing other ecosystem services, such as carbon storage and nutrients cycling to soil. Economic valorization of tree-pruning residues could also be an incentive for the implementation of agroforestry practices and landscape features. Further studies are needed in this relatively unexplored field, which might be of interest in the context of EU regulatory frameworks such as the EU Directive 2018/2001 and the upcoming Common Agricultural Policy (CAP) 2021 – 2027.

1. Introduction

According to the blue economy model proposed by Pauli (2010), it is necessary to find ways of utilizing physics, chemistry, and biology with renewable materials and sustainable practices just like ecosystems do. In this context, the technologies that mimic processes naturally occurring in ecosystems aim for a sustainable economic growth while avoiding the use of non-renewable natural resources and preserving ecosystems by implementing the blue economy model. Green technologies are an example of applying artificial processes for the same purposes (Ishak et al., 2017). Compost Heat Recovery Systems (CHRS) could be considered a technology that meets the blue economy principles, according to its characteristics. It is a plant for heating buildings and sanitary hot water by using the heat naturally produced during the composting of organic waste materials, that was made famous thanks to Jean Pain with his book *The Methods of Jean Pain: Another Kind of Garden* wrote in 1972 (Pain and Pain, 1972). It basically consists on a compost pile usually made up of a mixture of wood waste and manure, which contains a heat exchanger Zimmermann (2020). The external structure of the CHRS is usually made on iron welded mesh and insulated with straw bales, but depending on the on-site available materials, other containing and insulation system can be utilized. These plants are usually installed outdoor, due to their average dimensions (between 35 and 55 m^3) and their need for good ventilation. A waterproof membrane is needed on the bottom of the composting pile to prevent leachate produced during the process to percolate into the soil, and therefore to collect and recirculate it to keep the material moist.

Organic material inside the plant is biologically decomposed through microbial respiration, that is generally ascribed as the oxidation of organic matter to CO_2 by aerobic microbial communities (Babur et al.,

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2021). Under aerobic or micro-aerophilic conditions, molecular oxygen (O_2) plays a key role and is ultimately used as the terminal electron acceptor needed for microbial respiration, being a limiting factor for microbial growth (Zhou et al., 2020). Molecular oxygen is indeed the major electron acceptor on Earth and it is responsible for the oxidation of most of the organic matter (Chen and Strous, 2013), with the final production of carbon dioxide and water (Bindoli and Rigobello, 2013).

So, the basic process of the CHRS (the composting process) is a natural organic decomposition process controlled by a number of environmental conditions occurring in aerobic conditions, with the essential presence of oxygen that supports microbial activities (Wang et al., 2019). When organic materials are metabolized by microorganisms, O_2 is consumed and CO_2 is liberated, with amounts depending on the type of substrate, the environmental conditions and the microorganisms involved Stotzky (1965). Moreover, heat is metabolically generated according to the basic equation:

$$\begin{aligned} &Fresh\ organic\ waste + \ O_2\ \frac{microbial}{metabolism} \\ &\rightarrow stabilized\ organic\ residue + \ CO_2 + \ H_2O + heat \end{aligned}$$

(Finstein et al., 1986).

Irvine et al. (2010) reported average temperatures at the end of 12 days for 8 in-vessel composting tunnels (5-5.3 m wide and 25–35 m long with a height of 3 m) were consistently above 65 °C during spring, summer, and autumn, and around 60 °C during the winter months. These temperatures aligned with the values reported by Harper et al. (1992). Some studies have investigated the potential energy recovery from composting processes. According to Klejment et al. (2008), the heat that can be released during the high temperature phase of municipal waste is 1,136 kJ $\text{kg}_{\text{dry matter}}{}^{-1}$. Cumulative energy values reported by Ekinci et al. (2006) of 8,092 kJ $\text{kg}_{\text{dry matter}}{}^{-1}$ of biosolid waste and woodchip composting are similar to values reported by Irvine et al. (2010) that ranged from approximately 7,000 to 10,000 kJ $\text{kg}_{\text{dry matter}}{}^{-1}$ of green waste composting.

The heat produced inside the compost pile can be recovered through different systems. Numerous systems have been tested over the years and are described in great detail by Smith et al. (2016). In this case study, the CHRS was built according to the configuration pioneered by Pain (Pain and Pain, 1972), using a conduction-based approach to recover heat. In his configuration, coiled tubes are located within the composting mass and used to heat water flowing inside the tubes (Smith and Aber, 2017). Polyethylene pipes, filled with water, act as heat exchanger in the present case study. Pipes are placed in spirals at different eights of the compost pile. The heated water can be directly used for the underfloor heating system (UHS) of a building or be sent to the domestic hot water (DHW) accumulation tank and be directly used; otherwise, it can be stored in a boiler and then separated between UHS and DHW systems. Usually CHRSs are installed to heat building in combination with other heating systems, such as a pellet combustor or a heat pump. Zimmermann (2020).

Jean Pain composting systems have been investigated and modified in the years at pilot and full scales, under different names such as Biomeiler, thermocompost, bioreactor or composting reactor. However, scientific evidences and data about their life-cycle, performances and final compost quality are scarce in scientific literature (Bajiko et al., 2019).

In the EU, both European (2018/2001/EU) and member States' policies are promoting the use of renewable energy sources for new or renovated housing. In Italy, every building that is constructed or renovated from January 2018 on must use renewable energy sources to fulfill at least 50% of its energy needs (D. Lgs 28/2011). Indeed, our development, mainly based on non-renewable sources, is considered wrongful harm to future generations. It is vital therefore to establish a transition to a new model of development in response to the challenges of sustainability (Omri and Belaïd, 2020). Mitigation actions to limit the climate warming are indispensable to achieve a sustainable development (Allen et al., 2018). Climate warming can be limited through specific mitigation pathways such as energy-demand reductions, decarbonization of electricity and other fuels, electrification of energy end use, deep reductions in agricultural emissions and some forms of carbon dioxide removal with carbon storage on land or sequestration in geological reservoir (Rogeli et al., 2018). In this context, CHRS represents a viable alternative to the conventional centralized grid-connected power, to produce energy from residual biomass and organic waste, while providing effective solutions for waste management, as well as for dioxide removal with carbon storage on land and soil carbon pool restoration. With CHRS, biomass represents a sustainable and renewable energy source that could be exploited in small-scale plants for heat generation.

The functioning of a CHRS fed with woody biomass, lasts between 12 and 14 months on average; after that period the temperatures inside the pile decrease too much for an efficient energy recovery. In this real case study, thermal energy was recovered for 12 months. Native Power (www.native-power.de) and Biomeiler (www.biomeiler.nl), reported data about CHRS fed with woodchip, having dimensions of 55 and 70 m^3 respectively that lasted 1 year and 9 months respectively (cases similar to the CHRS studied in this research work). In his book, Pain and Pain (1972) reported a 75 m^3 CHRS fed with chipped brushwood that lasted 6 months and Zantedeschi reported the experience of Brown (2014), that implemented a CHRS of 31 m^3 that lasted 12 months Zantedeschi (2018). After these periods, the material converted into compost, has to be extracted from the body of the CHRS. This implies that the plant needs to be dismantled. During the biodegradation of biomass, the most recalcitrant (biologically resistant) fractions of organic matter is protected from enzymatic hydrolysis and microbial oxidation, which primarily constitutes the remaining 'compost' material. The production of compost is an added value for CHRS. Indeed, compost is a nowadays regulated product to use in agriculture (Pivato et al., 2017) as an excellent soil amendment to improve agricultural soil properties and organic contents (Huang et al., 2006). Being produced from organic waste, it contains organic matter and it is also rich in micro and macro-nutrients (Wang et al., 2019). Organic amendments improve crucial nutrients such as phosphorus and nitrogen, increase the water holding capacity and sorb metals, having an important impact not only on the soil physico-chemical properties, but also on the microbiological ones enhancing nutrient availability (Mazumder et al., 2021).

Also, after applying compost to the soil, the remaining carbon partially degrades further over longer periods (10–100 years) and at slower rates. Kranert et al. (2009) reported biodegradation yields about 85% of the initial content, along 50 years. Over a 100-year period, this figure was reported to still be in the range of 77–92% based on the available literature (Hermann et al., 2011; Franz et al., 2009). Over longer time-horizons, biodegradation is likely to follow a plateau-like trend, where a consistent fraction of organic carbon is preserved in soil. Compost production and application to agricultural soils as fertilizer is strongly recommended, as it encourages plant growth and healthy soil structure (Yun et al., 2019) increasing therefore agricultural productivity (Toumpeli et al., 2013). Many authors reported that compost has significant effect on soil nutrient improvement and plant growth enhancement (Bashir et al., 2020; Liu et al., 2019, Sorrenti et al., 2019). Its utilization could restore the soil quality and improve soil structure and fertility, which not only serves an important role in agricultural production but also is of great significance for improving the ecological environment (Yazdanpanah et al., 2016). Promoting soil productivity and improving the crop quantity and quality, compost utilization on soil can increase the income of the user (Wang et al., 2019). The use of a CHRS allows to produce compost material reusable on-site with related benefits.

The data recently reported in an Italian Ecopedological paper (MATTM, 2019), reported that soil quality is critical, especially in the Mediterranean area. Approximately 80% of Italian soils have an organic carbon content lower than 2% (ISPRA 2020). In this scenario, the restoration of the soil carbon pool is mandatory.

At the end of the process, when the plant needs to be dismantled and the compost is recovered, the CHRS can be simply rebuilt with new fresh biomass waste.

CHRSs thus present numerous advantages as it promotes the recovery and use of heat produced through the recycling of organic waste, which reduces CO_2 emissions while storing carbon inside compost material. At the end of the process compost can be applied to the soil restoring its carbon content, with the consequence of minimizing land degradation and soil erosion.

The focus of this work is to compare CHRS with different alternative heating technologies, under both economic and environmental points of view. Field data were collected from a full scale CHRS that operated for one year. Both green and traditional heating technologies were considered for the comparison. The green technologies were solar thermal panels and geothermal plant, while the traditional ones were pellet combustor and natural-gas condensing boiler.

Firstly, an economic analysis of the different systems was made, considering the full life-cycle of the plants combined in eight different scenarios. Next, for the environmental comparison between the different technologies was determined by comparing CO_2 emissions. Emissions related to the lifetime operation of the systems were estimated and compared to provide the total amount of CO_2 saved and stored due to the use of a CHRS instead of the other aforementioned solutions.

2. Materials and methods

This study was carried out using a real case study implemented in a farmhouse named Valbona located in Padua, Italy where a CHRS plant was built in 2017 and operated for a one-year period (March 2017 – March 2018). The system powered an UHS and heating of the DHW of the building, integrated with a pellet combustor to supply the entire amount of energy needed by the farmhouse.

The thermal power generated over one year by the CHRS was evaluated base on literature data and data coming from the short monitoring periods of a prototype plant.

Once the energy that can be provided by the CHRS was estimated, the remaining amount of energy needed by the farmhouse was considered to be provided by the pellet combustor. This solution represents a real case study. The other four technologies that were considered (i.e., solar thermal panels, geothermal plant, pellet combustor, and natural gas condensing boiler) were then designed and coupled in order to provide the total amount of energy needed by the farmhouse. A total of eight scenarios were compared to the real case study.

The cost of each technology was calculated along a lifetime of 15 years which started from the design phase and ended at dismantling. Moreover the $CO_{2\text{-eq}}$ *stored* and the CO_2 *saved* using renewable resources instead of fossil fuels (e.g., natural-gas) were estimated considering the operative lifetime of 15 years for each technology.

2.1. Case study: plant description and total energy demand

The case study refers to a CHRS installed in Valbona farmhouse, located in Lozzo Atestino (Padua, Italy), in the climate zone E. The zone has an average annual temperature of 12 °C and 770 mm of rainfall per year. The farm occupies around 20 ha of agricultural land where vegetables, fruits and vines are cultivated. Every year a considerable amount of pruning residues and other plant materials are produced and traditionally these materials were burned directly in the field or disposed without any kind of energy recovery. In 2017 an experimental plant for heat-recovery from the composting process was built and monitored. It consisted of a CHRS plant fed with the organic biodegradable green waste coming from the farmhouse gardening activities and maintenance. The system was designed and implemented in order to be connected to the UHS of the farmhouse and to provide the daily necessary DHW.

The CHRS is geometrically described by the parameters reported in Table 1 and its schematic is shown in Fig. 1. The system consists on a heap of raw biomass placed inside a cylindrical containing system made from fire mesh.

Table 1
Dimension of the heap of woodchips in the farmhouse.

Diameter (m)	5.00
Height (m)	2.80
Circumference (m)	15.70
Area (m^2)	19.63
Volume (m^3)	55.00

The raw biomass used inside the system was chipped, prior to placement, to an average size of approximately 1–2 cm.

Since the role of the CHRS plant is to recover the heat produced from the composting process and used to heat the farmhouse, it is necessary to limit the heat dispersion. Therefore, the heap was insulated using straw bales with a thickness of 0.5 m. The total diameter of the CHRS plant was 6 m. A polyvinyl chloride (PVC) sheet was placed at the bottom of the heap and some slotted polyethylene (PE) pipes, with an external diameter (D) of 120 mm, were used to collect the leachate that naturally forms during the composting process along with irrigation. This leachate was conveyed to a concrete tank. In order to enhance the microbial activity that takes place during the composting process, it is important to provide adequate conditions for microorganisms (aeration, C/N ratio, temperature, pH, moisture, etc.).

In order to control rainwater infiltration and provide the optimum humidity value (around 40–60%), a nylon cover was used to control rainwater infiltration. To ensure an adequate airflow, a slotted PE pipe with a diameter D of 120 mm pipe was placed at the center of the heap from the bottom to the top out from the heap. This setup allow aeration through the chimney effect.

Along the height of the woodchips, five different PE pipe coils, with an external diameter D of 32 mm and length of 100 m, were installed (total of 500 m of pipe) to act as heat exchangers. The five serpentines worked in parallel and were all connected to another PE pipe placed out from the heap. These pipes were thermally insulated with the plastic material normally used for district heating systems.

The water flowing inside the pipes was heated through the heat developed by the CHRS, collected inside the external insulated PE pipe and transferred to a connected puffer located inside a room of the farmhouse. The hot water generated inside the puffer was then distributed as DHW and for use in the UHS. Once the heat exchange took place, the water in the coil was cooled and returned to the CHRS. The connection circuit between the CHRS and the puffer was hence closed.

At the farmhouse, the UHS covered the spatial heating for a surface of 275 m^2 and the daily DHW demand equal to 2,000 L day^{-1} (ρ = 1 kg L^{-1}). The daily water demand was based on the needs of the restaurant kitchens and the bathrooms of the house including both hostel and private uses. The energetic class of the farmhouse was estimated as a “Class E” (i.e. annual consumption for heating of around 100 kWh m^{-2} according to Italian D. Lgs. 102/2014). Therefore, the annual energy consumption for the UHS (E_{UHS}) was estimated using the following equation:

$$E_{UHS} = S * H = 275\ m^2 * 100 \frac{kWh}{m^2 year} = 27,500\ kWh\ year^{-1} \quad (1)$$

where: S is the surface of the heated floor (m^2) and H is the annual consumption for heating (kWh m^{-2} $year^{-1}$) according to the specified energetic class.

The annual energy consumption for the DHW was estimated as follows:

$$\begin{aligned} E_{DHW} &= M_w * c_p * \Delta T \\ &= 2000 \frac{kg}{day} * 365 \frac{day}{year} * 1 \frac{kcal}{kg\ °C} * 50°C * 0,00116 \frac{kWh}{kcal} \\ &= 42,340\ kWh\ year^{-1} \end{aligned} \quad (2)$$

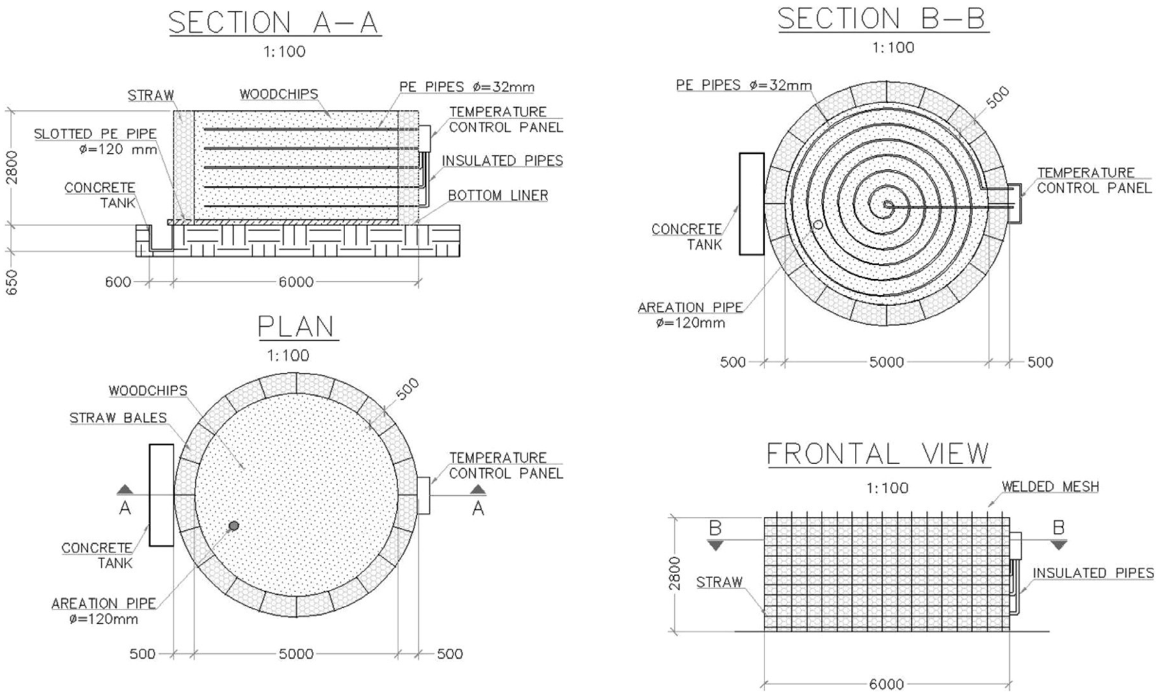

Fig. 1. CHRS plant scheme.

Table 2
Thermal power output data collection from different on-field prototypes of CHRSs.

Composted material	Average power	Energy recovered		Monitoring time	Volume	Reference
	kW m^{-3}	MJ m^{-3}	MJ $kg_{biomass}^{-1*}$	days	m^3	
Woodchips	0.047	1,462	3.7	365	55	www.native-power.de
Woodchips	0.053	1,236	3.1	270	79	(Biomeiler 2020)
Woodchips	0.156	404	1.0	30	16	Zantedeschi, 2018
Chipped brushwood	0.19	2,955	7.4	180	75	Pain and Pain, 1972
Chipped brushwood	0.02	467	1.2	270	197	Schuchardt, 1984
Horse manure, sawdust, woodchips	0.14	302	0.8	25	0.9	Chambers, 2009
Bamboo	0.06	218	0.5	42	50	Seki et al., 2014
Woodchips	0.09	2,799	7.0	365	31	Brown, 2014
Horse manure, woodchips, fresh grass	0.10	311	0.8	36	6.7	Bajko et al., 2019
Cow manure, grass, sawdust	0.20	225	0.6	13	2.8	Mwape et al., 2020
Green waste	0.10	3,11	7.8	365	60	Cuhls et al., 2020 ***
Green waste	0.10	3,11	7.8	365	150	Culhls et al., 2020 ***

*considering a biomass density of 400 kg m^{-3}
**energy recovery calculated turning kW m^{-3} into kWh m^{-3} and then turning kWh into MJ (conversion factor 3.6 MJ kWh^{-1})
***Cuhls et al., quoted by Zimmermann (2020). Cuhls' reference not available

where: M_w is the daily mass of DHW required (kg day^{-1}), c_p is the specific heat capacity of water (kcal kg^{-1}°C^{-1}), ΔT is the temperature difference between the hot water in the buffer and the cold water from aqueduct (°C).

Thus, the total yearly energy requirement (E_r) of the farmhouse was calculated as the sum of the annual energy consumption for the UHS and DHW production:

$$E_r = E_{UHS} + E_{DHW} = 69,840\ kWh\ year^{-1} \tag{3}$$

The thermal power generated over time by the CHRS was then evaluated base on the literature data as well as data coming from short monitoring periods of the prototype plants. The values of the thermal power output depends on many aspects related to the kind of organic material used inside the plant, its volume, and the duration of the process. All the values found in the literature are reported in Table 2 and described later on in more detail. Moreover, a pilot plant was monitored for one month in February 2018 and provided another results about the thermal power of woodchip materials undergoing aerobic biodegradation (Table 2). The pilot plant was monitored collecting data four times a day, one day a week, with a heat meter installed on the piping system. Every measure was taken in the middle of the 15 minutes operating time. The final thermal power value was calculated as the mean obtained considering the frequency (f_i) over every value of power (P_i), as follows:

$$\sum P_i * f_i / total\ number\ of\ measurments \text{ Zantedeschi (2018)} \tag{4}$$

The mean value between the different thermal power values collected from literature and from the pilot plant monitoring, was used to estimate the total energy amount that can be supplied through the CHRS.

According to this estimation, it turned out that part of the total annual energy demand could be supplied through the CHRS. The remaining energy needed by the farmhouse is provided through a pellet combustor.

2.2. Design of heat sources chosen for comparison

Alternative technologies for heat production were taken into consideration to compare the performance of the CHRS and to evaluate if it is beneficial in terms of the energy provided, considering the related costs and CO_2 emissions. The latter were determined through a cost analysis and a carbon balance.

The technologies compared to the CHRS were two green technologies involving renewable resources (solar thermal panels and geothermal plant) and two alternative traditional technologies (pellet combustor and natural-gas condensing boiler).

Technologies were designed and/or combined in order to provide the same total amount of energy supplied in the real case study involving a CHRS and a pellet combustor which is 69,840 kWh y^{-1}.

Each technology was designed with further assumptions and calculations:

The solar thermal system was designed to evaluate the number of solar panels necessary to provide the same amount of energy supplied by the CHRS system of the case study. The system design was carried out by applying the good-practice guidelines discussed by theDeutsche Gesellschaft fur Sonnenenergie - German Solar Energy Society guide for Installers, Architects and Engineers (DGS 2005). To calculate the required area of the solar collector, A (absorber surface area, m^2), the following equation was used:

$$A = \frac{E_r}{E_G * \eta_{SYS}} \tag{5}$$

where: E_r is the yearly heat requirement (kWh y^{-1}), E_G is the yearly potential solar irradiance (kWh m^{-2} $year^{-1}$) (Lozzo Atestino: $E_{G=}$1,421 kWh $m^{-2} year^{-1}$, source: Solar Panels – information about Solar and Photovoltaic Panels, http://www.infopannellisolari.com/), and η_{SYS} is the average system efficiency, which is the ratio of solar heat yield to global solar irradiance experienced by the absorber surface (0.35 for flat plate collector or 0.45 for an evacuated tube collector). The average system efficiencies used take into account losses at the collector, solar circuit, and storage (Irvine et al., 2010).

Regarding the other green technology, a geothermal system with vertical wells was designed. The length of the closed-circuit pipes placed in the boreholes linked to the heat pump (geothermal probes), where heat transfer fluid flows inside. Almost all the methods are based on the synthetic relationship for steady-state heat exchange (De Carli et al., 2003):

$$L = \frac{Q * R}{T_g - T_w} \tag{6}$$

where: L is the total length of the pipes (m); Q is the average heat flux exchanged between the heat transfer fluid of the single probe and ground (W); R is the equivalent thermal resistance offered by the ground per unit of probe length (0.25 m K W^{-1}); T_g is the average subsoil temperature not influenced by the presence of the probe (14 °C); T_w is the average temperature of the heat transfer fluid that supplies the geothermal probe (6 °C).

The average annual thermal load absorbed or released from the ground is calculated as follows:

$$Q_a = \frac{q_{lc} * \frac{COP_c + 1}{COP_c} * h_c \; + E_r * \frac{COP_h + 1}{COP_h}}{8760} \tag{7}$$

where: q_{lc} is the project load necessary for cooling the building (W); E_r is the project load needed to heat the building (Wh); h_c are the equivalent hours at full load (ratio between the seasonal energy requirement and the maximum power) and 8760 is the total hours in a year. The values of COP_c and COP_h (Coefficient Of Performance, related to cooling and heating), are chosen based on the temperature of the heat pump input (design data) and calculated according to UNI TS 11300-4:

$COP_c = T_1/(T_2-T_1)$ and $COP_h = T_2/(T_2-T_1)$ where T_1=cold spring temperature and T_2=hot spring temperature.

The advantage of the heat pump consists is the fact that it can be used both for heating and cooling a house. However, in this case-study, only the heating process was considered in order to have a meaningful comparison between geothermal plant technology and CHRS technology.

Last two technologies are pellet combustor and natural-gas condensing boiler. For the pellet combustor, the amount of pellets that are necessary to provide the same amount of heat recovered with the CHRS system was determined. The amount of pellet (M_p) in kilograms, was calculated on the basis of the pellet calorific value which will depend on the different kinds of pellets.

$$M_P = \frac{E_r}{LHV * \eta_c} \tag{8}$$

where LHV is the pellet lower heating value (net calorific value) and η_c is the assumed combustor efficiency.

Lastly, a natural-gas condensing boiler was considered. Knowing the calorific value of methane and assuming a certain boiler efficiency, the volume of natural gas (V_{gas}) necessary to generate the same amount of energy provided by the CHRS system can be calculated as follows:

$$V_{gas} = \frac{E_r}{LHV * \eta_b} \tag{9}$$

where: LHV is the natural gas lower heating value (net calorific value) and η_b is the assumed boiler efficiency.

Once the design of the plant was completed to ensure the same amount of energy was provided in the real case study, a cost analysis and a carbon balance was carried out in order to evaluate the advantages and disadvantages (if applicable) related to CHRSs in terms of cost savings and CO_2 stored.

2.3. Definition of alternative scenarios

The alternative scenarios were selected and evaluated in order to provide a total amount of energy of 69,840 kWh y^{-1} required by the farmhouse. Since the CHRS is able to provide a total amount of energy per year equal to 24,090 kWh, the alternative ways to supply energy through renewable resources (e,g,m green technologies: solar thermal panels and geothermal plant) were designed in order to provide the same amount of energy of the CHRS, combined with traditional technologies (pellet combustor and natural-gas condensing boiler) able to supply the remaining amount of energy (45,750 kWh y^{-1}) necessary to reach the total energy requirements.

A total of 9 scenarios were compared. Case A represents the current situation of the farmhouse, equipped with a CHRS and a pellet combustor to supply the annual energy requirement for DHW and UHS. Each scenario was analyzed under an economic point of view in order to evaluate the economic benefits that can be provided by the use of a CHRS instead of other alternatives including both renewable and traditional technologies. First two cases (B and C) represent the alternatives using green technologies solar thermal panels and geothermal plant integrated with a pellet combustor similar to the real case. Second two cases (D and E) represent the alternatives using green technologies which were solar thermal panels and a geothermal plant integrated with another traditional technology, instead of Pellet combustor, a natural gas condensing boiler was used in order to provide the same amount of energy as the pellet combustor (45,750 kWh y^{-1}). Therefore, the first four cases were similar to the real case; renewable technologies are used to provide the same amount of energy provided by the CHRS (24,090 kWh y^{-1}) and the remaining energy needed by the farmhouse is supplied by two different traditional technologies, pellet combustor and natural gas condensing boiler. In the fifth and sixth cases (F and G), the entire energy needed by the farmhouse was provided by a single traditional technology was been considered (for the pellet combustor and for the condensing natural gas boiler). Lastly, two alternative uses of the CHRS have also been considered. Case H is represented by a CHRS integrated with a natural-

Table 3
Summary of the 9 considered scenarios, represented by a combination of two plants, with the exception of cases F and G made on one single plant; all 9 scenarios provide 69,840 kWh y^{-1}(STP=Solar Thermal Panels, GTP=Geothermal Plant, PC=Pellet Combustor, NGCB=Natural-Gas Condensing Boiler).

SCENARIOS	PLANT 1		PLANT 2	
	TYPE	ENERGY PROVIDED	TYPE	ENERGY PROVIDED
CASE A – REAL CASE	**CHRS**	**24,090 kWh y^{-1}**	**PC**	**45,750 kWh y^{-1}**
CASE B	STP	24,090 kWh y^{-1}	PC	45,750 kWh y^{-1}
CASE C	GTP	24,090 kWh y^{-1}	PC	45,750 kWh y^{-1}
CASE D	STP	24,090 kWh y^{-1}	NGCB	45,750 kWh y^{-1}
CASE E	GTP	24,090 kWh y^{-1}	NGCB	45,750 kWh y^{-1}
CASE F	PC	69,840 kWh y^{-1}		
CASE G	NGCB	69,840 kWh y^{-1}		
CASE H	CHRS	24,090 kWh y^{-1}	NGCB	45,750 kWh y^{-1}
CASE I	2 CHRSs	50,000 kWh y^{-1}	PC	19,840 kWh y^{-1}

gas condensing boiler providing the same amount of energy provided by the pellet combustor in the real case (A).

While Case I is represented by two CHRSs providing the double amount of energy provided by a single CHRS in the real case A (more or less 50,000 kWh y^{-1}) integrated with a pellet combustor, so same situation of the real case considering to use two CHRSs.

In Table 3, a summary of the eight scenarios compared to the real case is presented. Except for cases F and G, all the others are made on the combination of two plants (Plant 1 and Plant 2). In the real case A, plant 1 is represented by the CHRS supplying 24,090 kWh y^{-1} and plant 2 by the traditional pellet combustor supplying 45,750 kWh y^{-1}.

For all cases, the initial costs (design, installation and materials), the dismantling costs and annual operating costs are compared and assessed over an average plant-life of 15 years. This time-scale ensures the CHRS is truly a convenient alternative heating-system for domestic use.

2.4. Cost analysis and carbon balance analysis

To understand the economic advantage of the CHRS, a comparison with other technologies along a 15-years period was completed. For each technology the capital costs and the annual operating costs are reported. A generic item of cost/profit is determined by applying the following expression:

$$Item\ cost\ = q * unit\ price \tag{10}$$

where: q is the quantity (reference unit) and unit prices (€ reference unit^{-1}) were taken from different sources: the price list of Veneto Region (Veneto Region Price list, 2018) and many catalogues of different companies specialized in the production of heating systems. The considered prices do not include VAT and tax incentives. Natural-gas price and electric energy prices are based on data from Autorità di Regolazione per Energia Reti e Ambiente (ARERA 2020)

During the cost analysis, radiant panels of UHS, puffers, recirculation pumps and expansion vessels' have not been taken into account, due to the fact that their price can be considered similar for each considered system since they are included in every case.

The costs related to eight different alternative scenarios made based on the combination of different technologies able to provide the total amount of energy needed yearly by the farmhouse (69,840 kWh y^{-1}) were considered and compared to the real case study (case A).

At the same time, a carbon balance analysis was performed. To evaluate the carbon stored in the compost material and seized from potential emissions, it was necessary to evaluate the degradation rate of the CHRS in order to determine the amount of compost obtained.

To evaluate the degradation rate of the plant, compost samples were taken from the CHRS at the end of the year and analyzed at the laboratory of Sanitary Engineering of the University of Padua and were compared to other laboratory analyses conducted on a mixture of biomass (i.e., fine grained woodchips, coarse woodchips and acacia wood scraps) that well simulate the composition of the woodchip heap inside the CHRS, subjected to aerobic biodegradation process.

During the laboratory analyses conducted on the mixture of biomass, the initial and final amount of Dry Matter (DM) and of Volatile Solids (VS) were measured. The aerobic biodegradation test lasted 240 days (8 months) and was carried out as follow: 5 g of each dry biomass were placed in a plastic laboratory-scale vials with 12,5 g of solid digestate (inoculum) and 20 mL of distilled water. To allow for the presence of oxygen, every tap contained some holes. In addition to the other tests, two white blanks were prepared, containing only solid digestate and water, to understand how much the inoculum would have affected the biomass degradation. All the reactors were kept at a constant temperature of 40 °C.

Since the values of the VS of the samples taken from the CHRS represent the values of the VS measured at the end of the 8 month lab tests were similar, it was assumed the degradation efficiency obtained from the 8 month lab tests were valid and could be applied to the CHRS.

The biodegradation efficiency on the VS was calculated as follows:

$$\eta_{SV} = 1 - \frac{m_{VS}}{M_{VS}} \tag{11}$$

where: m_{VS} is the final mass of VS after 240 days of the lab scale aerobic biodegradation test (kg); M_{VS} is the initial mass of VS (kg) before the lab test.

At the same time, the degradation efficiency on the DM was calculated as

$$\eta_{DM} = 1 - \frac{m_{VS}}{M_{DM}} \tag{12}$$

where: M_{DM} is the initial mass of the dry sample (kg).

2.4.1. CO_2 stored and CO_2 saved

Carbon sequestration from the potential emissions to atmosphere that are avoided is defined as a carbon-sink. Compost produced by the CHRS acts as a carbon-sink, since part of the carbon content is not degraded during the aerobic process and it remains stored in the soil. The carbon that could be stored was considered as an important added value related to the implementation of this technology and was estimated as follows

$$CO_2 - eq = OC * X * \frac{MW_{CO2}}{MW_C} \tag{13}$$

where: OC is the organic carbon contained in compost ($kg_C\ t_{DM}{}^{-1}$); X is the compost content of non-degraded organic carbon (%); MW_{CO2} is the CO_2 molecular weight ($kg_{CO2}\ kmol^{-1}$); MW_C is the carbon molecular weight ($kg_C\ kmol^{-1}$).

Regarding the amount of CO_2 saved, starting from the idea that different energy providing systems are related to different CO_2 emission amounts, it is also possible to evaluate the CO_2 saved (i.e., air emissions in terms of CO_2 avoided) implementing the CHRS respect to the use of the considered alternatives.

The total amount of emissions should be estimated as the sum of the direct and indirect emissions, concerning all the life-cycle aspects of the considered plants (e.g., emissions related to source extractions,

Table 4
Dimensioning of the different plants to provide the necessary amount of energy required by the farmhouse (STP=Solar Thermal Panels, GTP=Geothermal Plant, PC=Pellet Combustor, NGCB=Natural-Gas Condensing Boiler).

PLANTS	ENERGY TO PROVIDE (yearly)		DESIGN	
STP	24,090	kWh y^{-1}	25	n of panels
GTP	24,090	kWh y^{-1}	326	meters (probes)
PC	45,750	kWh y^{-1}	10,770	kg of pellets
	69,840	kWh y^{-1}	16,430	kg of pellets
	19,840	kWh y^{-1}	4,670	kg of pellets
NGCB	45,750	kWh y^{-1}	5,300	Sm^3 of natural gas
	69,840	kWh y^{-1}	8,083	sm^3 of natural gas

plants production, transport, installation, operative time, dismantling and final disposal). In order to do that, a complete life cycle assessment for each plant should be completed.

Since this is not the main goal of this study, this study only considered the operative lifetime in order to provide an idea about the CO_2 air emissions that can be avoided during 15 years of operation due to the use of a CHRS.

For each system (CHRS, pellet combustor, natural-gas condensing boiler, solar thermal panels and geothermal plant), the specific emission factors in kg of CO_2 emitted per kWh according to literature data were considered. After which, the total amounts of CO_2 emitted in 15 years for producing the required energy (69,840 kWh y^{-1}) was calculated for each of the eight scenarios:

$$CO_{2-p} = emission\ factor *\ E_r * 15 \tag{14}$$

where the emission factor is expressed in $kg_{CO2\text{-}eq}$ kWh^{-1} and E_r is the yearly heat requirement in kWh y^{-1}.

Emission factors from the literature were considered to carry out all of the calculations. They were mainly taken from an ISPRA report about CO_2 and other greenhouse gases emission factors in the electricity sector Caputo (2017). These reports also stated that emissions related to the combustion of pellets, was negligible. A similar conclusion was reported at the UNFCCC convention (United Nations Framework Convention on Climate Change) for the calculations of the atmospheric CO_2 emissions, from the combustion of biomasses. The reason for this conclusion is the CO_2 emitted during the combustion process is equal to the CO_2 absorbed during the life of the plant used through the photosynthesis process.

Since this work did not include a complete life cycle but just the operative period of the plants, an emission factor related to just to the combustion of the pellets was necessary for the calculation of the emissions due to the use of this combustor. The factor was taken from a report by AECOM commissioned in 2010 by the Zero Carbon Hub (Lelyveld and Woods, 2010). The calculation of the emissions related to the use of gasoil for pellet transport and for the chipper machine, the emission factor was taken from the APAT report about the CO_2 emissions from the transport sector (Contaldi and Ilacqua, 2003).

Firstly, the total amount of CO_2 produced per kWh of energy provided using each one of the five considered plants (CHRS, solar thermal panels, geothermal plant, pellet combustor and condensing natural gas boiler) was estimated. Next the total kg of CO_2 produced over 15 years for each of the eight scenarios were calculated and compared. The emissions related to the use of electricity for powering the water circulation pump was not taken into account due to the fact that they are the same for each system.

To calculate the CO_2 emissions related to the implementation of the CHRS and pellet combustor as well as the emissions related to the use of gasoil for wood-material chipping and for pellet transport respectively were considered. Due to the fact that during the operative lifetime of these plants it is necessary to produce (for the CHRS) and to transport (for the pellet combustor) biomass material, the emission factor expressed in $kg_{CO2\text{-}eq}$ $kg_{gasoil}{}^{-1}$ was multiplied for the kg of gasoil necessary to power the chipper machine and the van.

The final values obtained in terms of $kg_{CO2\text{-}eq}$ kWh^{-1} were compared to determine how much CO_2 can be saved.

3. Results and discussion

3.1. Energy supplied by CHRS

To evaluate the energy provided by the CHRS, literature data and 1-month monitoring pilot plant data for the thermal power output related to woodchip material subjected to an aerobic biodegradation process were used.

Literature data were related to different case studies of thermal power production from aerobic biodegradation of woodchip material or a similar material. The different values reported, reflects different situations in terms of the duration of the energy supply which is the amount of material undergoing the aerobic biodegradation and the type of material used.

The duration of the energy supply of the considered case studies, is between 13 days and 18 months, with a thermal power varying from 0.02 kW m^{-3} for a 9 months lasting process for 197 m^3 of material (Schuchardt, 1984) to 0.2 kW m^{-3} for a 13 days process for 2.8 m^3 of material (Mwape et al., 2020).

The one month 16 m^3 pilot plant monitoring period provided a mean thermal power output of 0.156 kW m^{-3} (Zantedeschi, 2018)

Further data and information were collected from the Native Power Organization and Biomeiler, which are both commercial enterprises that focus on woodchip composting to propose a list of preferable dimensions based on their experience in order to maximize heat production starting from an available volume of woodchip.

According to all of the values reported in Table 2, a power value equal to 0.05 kW m^{-3} was used since it aligned most closely to the real cases implemented are the farmhouse.

The energy of the farmhouse CHRS case-study was estimated as follows:

$$Q_t = 0.05\frac{kW}{m^3}*55\ m^3*24\frac{h}{d}*365\frac{d}{year} = 24,090\ kWh\ year^{-1} \tag{15}$$

Considering that the annual energy consumption of the farmhouse is 69,840 kWh y^{-1}, for UHS and DHW, the CHRS was estimated to achieve around 34.5% of the energy needed by the farmhouse.

3.2. Economic evaluations

To evaluate costs related to the alternative technologies chosen to carry out the comparison, the technologies were designed in order to supply different amount of energy. Solar thermal tanels and the geothermal plant were both designed to supply the same amount of energy provided yearly through the CHRS in the real case study (24,090 kWh y^{-1}), while pellet combustor and natural-gas condensing boiler were designed to supply the remaining amount of energy provided by a Pellet Combustor in the real case study (45,750 kWh y^{-1}); moreover, they were designed to supply the entire amount of energy required yearly by the farmhouse (69,840 kWh y^{-1}). Moreover, the pellet combustor was considered to supply the remaining amount of energy required by the farmhouse when two CHRSs are installed instead of just one (19,840 kWh y^{-1}).

The dimensioning of each plant are summarized in the table below (Table 4). Supplementary data and formulas are provided in Supplementary materials – Plants design).

Dimensions in Table 4 were used to perform the economic analysis and to provide an idea about the economic advantages related to the implementation and use of the CHRS.

Once the different plants were designed in order to provide the necessary amounts of energy, the plants were combined in the eight alternative scenarios (case B, C, D, E, F, G, H and I) and were analyzed under an economic point of view. All the metric computations carried out for each plant are reported in Supplementary materials – Plants cost.

After that, the total costs resulted for each scenario were compared to the costs related to real case (Case A). These results are outlined in Table 5. The costs per kWh of energy generated are based both on the initial capital costs and the operating costs required to run the system over a 15 year lifetime.

As shown in Table 5, all the capital and operational costs related to each scenario over the entire operative lifetime are provided and the units costs are expressed in € per kWh for each system. CHRS is advantageous with respect to the other plants from a renewable energy perspective in terms of the construction and dismantling stages. Regarding the operative lifetime, the costs are in line with other green technologies. But it turned out to be cheaper than other traditional technologies. The operational costs of the CHRS are mainly related to the costs of the raw material used to fill the CHRS (12 € m^{-3}, which means 0.03 € kg^{-1} considering a woodchips density of 400 kg m^{-3}). These aforementioned costs are necessary if not enough green waste is available from the farmhouse at any given time.

To carry out the economic evaluation, the maintenance of the CHRS was assumed to be done once per year. Regarding the materials, the real case turned out to be much cheaper than other solutions involving the other green technologies. Moreover, the items used for building the CHRS (e.g., welded mesh, PE pipes) can be reused after dismantling. This means that after the first lifetime period of 15 years, the system can be re-built without requiring to spend more money for material (just organic material and labor related costs). Looking at the unit costs in € kWh^{-1}, to implement the real Case A with one CHRS and one pellet combustor is not the cheapest case but considering Case I with two CHRSs and the remining energy supplied by a pellet combustor, this turned out to be the cheapest solution.

In regards to the other two green technologies solar thermal panels and geothermal plant, the cases involving these two plants (Cases B, C, D, and E) showed that the capital costs are higher than other solutions especially due to materials and construction phase costs. At the same time, solar thermal panels have lower operational costs respect to the average, due to the fact that they just need to have a substitution of the inverter/cleaning after ten years for an estimated cost of about 120 € (Cases B and D). Regarding the cases involving the geothermal plant, the construction phase is very costly due to the perforations into the ground and the price of the heat pump (about 10 thousand €). Also the operational costs are quite high in Cases C and E because of the energy required by the heat pump compressor.

Regarding only the use of the traditional systems pellet combustor and natural-gas condensing boiler (Cases F and G), the greatest part of the costs is represented by the operational phase due to the costs of the pellets and of the natural gas, respectively.

To assess which is the most convenient solution, the unit costs of each scenario were evaluated considering the lifetime of 15 years and considering the total amount of energy to be provided (69,840 kWh y^{-1}).

In Fig. 2, the total costs related to capital costs and operating costs over 15 years are shown (in €) for each one of the eight scenarios.

It can be seen that the lowest unit cost turned out to be the one related to Case I (0.074 € kWh^{-1}). Therefore, implementing two

Table 5
Cost of the different evaluated scenarios to supply the total annual energy demand of 69,840 kWh of Valbona Farmhouse (CHRS=Compost Heat recovery System, PC=Pellet Combustor, STP=Solar Thermal Panels, GTP=Geothermal Plant, NGCB=Natural-Gas Condensing Boiler).

	SCENARIOS	Case A REAL CASE CHRS 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}	Case B STP 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}	Case C GTP 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}	Case D STP 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}	Case E GTP 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}	Case F PC 69,840 kWh y^{-1}	Case G NGCB 69,840 kWh y^{-1}	Case H CHRS 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}	Case I 2 CHRSs 50,000 kWh y^{-1} + PC 19,840 kWh y^{-1}
CAPITAL COSTS €	DESIGN	1870.00	1429.15	4885.27	1429.15	4885.27	0.00	0.00	1870.00	1870,00
	CONSTRUCTION	2473.16	3497.56	11368.84	3305.32	11176.60	457.24	265.00	2280.92	3715,40
	MATERIAL	8786.00	25281.59	34642.67	21881.59	31242.67	4782.56	1382.56	5386.00	12789,44
	DISMALNTLING	328.28	2177.43	848.68	2177.43	848.68	121.24	121.24	328.28	949,40
OPERATIONAL COSTS (€) in 15 Years		77512.93	55267.06	73448.80	63587.51	81769.25	81361.41	94284.21	85833.38	58099,22
UNIT COSTS (€ kWh^{-1}) in 15 Years		**0.087**	**0.084**	**0.120**	**0.088**	**0.124**	**0.083**	**0.092**	**0.091**	**0.074**

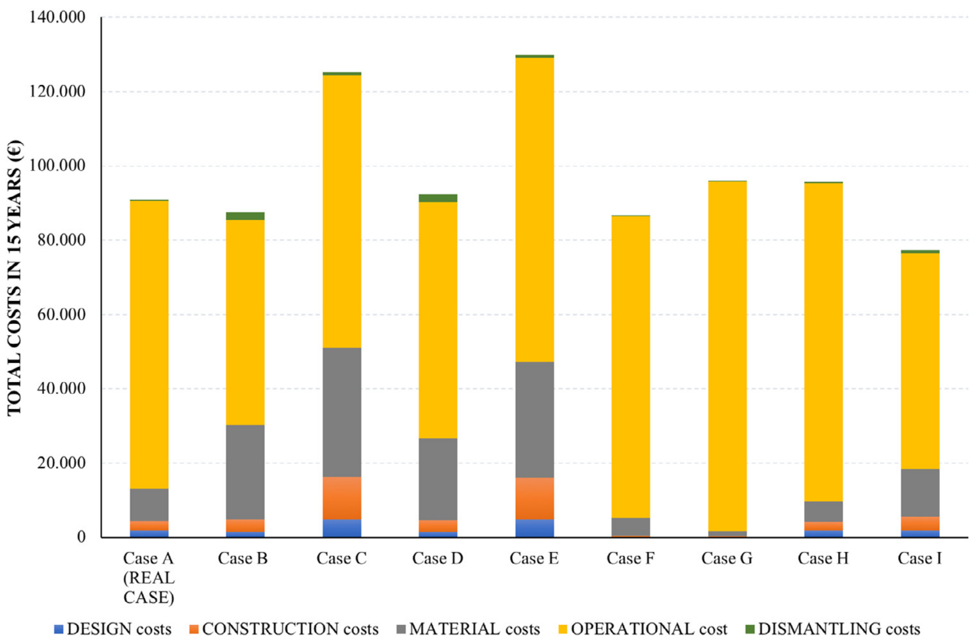

Fig. 2. Total costs in 15 years (design + construction + material + operational + dismantling) of the different scenarios, compared considering a total amount of energy provided to the farmhouse per year of 69,840 kWh. (Case A = CHRS + Pellet Combustor, Case B = Solar Thermal Panels + Pellet Combustor, Case C = Geothermal Plant + Pellet Combustor, Case D = Solar Thermal Panels + Natural-Gas Condensing Boiler, Case E = Geothermal Plant + Natural-Gas Condensing Boiler, Case F = Pellet Combustor, Case G = Natural-Gas Condensing Boiler, Case H = CHRS + Natural-Gas Condensing Boiler, Case I = 2 CHRSs + Pellet Combustor).

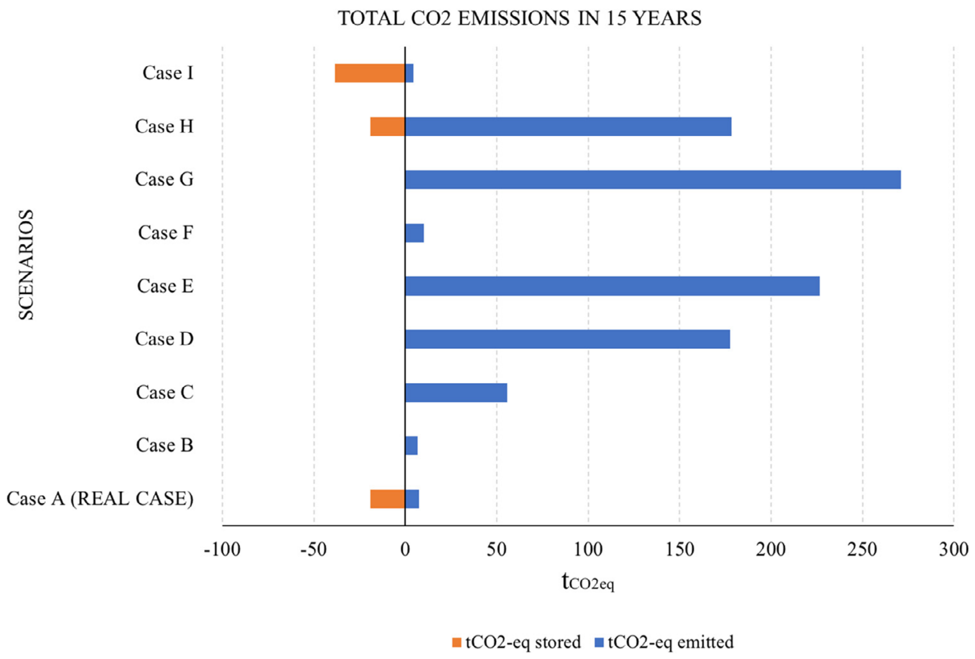

Fig. 3. Total CO_2 emissions in $t_{CO2\text{-eq}}$ related to the utilization of the different plants in each scenario, providing Valbona farmhouse the necessary annual energy of 69,840 kWh, calculated for the operative time, in 15 years. (Case A = CHRS + Pellet Combustor, Case B = Solar Thermal Panels + Pellet Combustor, Case C = Geothermal Plant + Pellet Combustor, Case D = Solar Thermal Panels + Natural-Gas Condensing Boiler, Case E = Geothermal Plant + Natural-Gas Condensing Boiler, Case F = Pellet Combustor, Case G = Natural-Gas Condensing Boiler, Case H = CHRS + Natural-Gas Condensing Boiler, Case I = 2 CHRSs + Pellet Combustor)

CHRSs providing 50,000 kWh y^{-1} and supplying the remaining energy (19,840 kWh y^{-1}) with a pellet combustor, is the most economical convenient solution. This study thus demonstrated that implementing a CHRS results in a significant cost savings. While involving a geothermal plant, even if it can be considered a sustainable alternative (Moya et al., 2018), according to the results obtained in this study, is not economically advantageous for domestic heating relative to any of the proposed solutions.

3.3. *Mass and carbon balance*

To evaluate the amount of carbon produced and the amount of carbon stored in the compost, it was necessary to evaluate the degradation rate of the plant. In order to do that, compost samples were taken from the farmhouse CHRS plant and were collected are three different points of the system (i.e., at the end of the process and at a depth of 70–80 cm) and were analyzed at the Laboratory of Sanitary Engineering of the University of Padova.

These samples were compared to the lab scale test lasted 8 months previously explained. Comparing the values of the VS at the end of the biodegradation process of both cases, it was determined that the final VS of the samples taken from the real CHRS and the final VS of the lab test biomass were similar, as reported in Table 6. Therefore, the rate of degradation obtained from the lab tests would also be valid for the real CHRS. Therefore, the degradation efficiencies of the biomass of the 8 months lab test calculated on VS and DM (Table 7) were also assumed to be valid for the real CHRS plant. The average degradation efficiency for the CHRS was 49.8% on the DM and that the compost formed during the composting process was the remaining 50.2 % (on DM basis relative to the initial feedstock).

The compost obtained from the CHRS contributes to maintaining the organic carbon content of the soil at or above values normally present in

Table 6
Volatile solids contents of mixed biomasses simulating CHRS material after 8 months aerobic biodegradation lab test and VS % of Valbona's CHRS compost samples collected after 12 months of activity.

Material	Time of degradation (months)	Volatile solids ($g\ g^{-1}{}_{DM}$)
Fine-grained woodchips	8	67.6
Coarse woodchips	8	81.4
Acacia wood scraps	8	73.1
woodchips from CHRS - north sample	12	74.0
woodchips from CHRS - south sample	12	81.0
woodchips from CHRS - middle sample	12	88.0

Table 7
Efficiency of degradation of mixed biomasses simulating CHRS material from lab test lasted 8 months.

Material	Degradation Efficiency on VS (%)	Degradation Efficiency on DM (%)
Fine-grained woodchips	60.4	66.3
Coarse woodchips	15.5	27.1
Acacia wood scraps	49.6	55.9
Average	41.8	49.8

nature. With the estimated degradation efficiency, the amount of compost obtained at the end of the process occurring inside the CHRS and the amount of carbon that can be stored were calculated as follows.

Considering that the density of woodchips with the 45% of humidity is equal to 400 kg m^{-3} ((AIEL 2021)), the total amount of dry matter into CHRS will be:

$$M_w = 55\ m^3 * 400 \frac{kg_{FM}}{m^3} * 0.55 \frac{kg_{DM}}{kg_{FM}} = 12,100\ kg_{DM} \tag{16}$$

Since the efficiency of degradation of woody materials tested in laboratory experiments (data reported in paragraph 3.1) resulted 49.8% on the dry matter, the remaining woodchip material after degradation occurs, will be 50.2% of its initial dry weight, therefore the amount of compost produced can be considered equal to:

$$M_C = M_w * 0.502 = 12,100 * 0.502 = 6,074.2\ kg_{compost} \tag{17}$$

The amount of compost produced was useful to calculate the amount of carbon in terms of CO_2-eq stored in the soil over long periods by applying the produced compost to the soil.

3.3.1. CO_2 stored and CO_2 saved

According to Suzuki et al. (2004), the organic carbon fraction in mature compost (recorded after 10 months of the composting process) from swollen chipped wood is 37%. Using this value, the amount of organic carbon stocked in the compost was calculated as follows:

$$Cs = M_C * 0.37 = 6,074.2 * 0.37 = 2,247.5\ kg_C \tag{18}$$

After application of the compost to soil, the carbon will partially degrade over longer periods (10–100 years). According to Hermann et al. (2011), approximately 23% of the organic carbon remains in the soil as humus. Considering the same period of time, according to Franz et al. (2009), about 8.2% of the organic carbon supplied with the compost would still be available in the soil. In order to calculate the carbon stored in the soil over 100 years related to this case study, an average value of 15.5% was considered:

$$C_{stored} = Cs * 0.15 = 2,247.5 * 0.15 = 348.4\ kg_C \tag{19}$$

Which correspond to 57.4 $kg_c\ t^{-1}$ of compost. In terms of kg of CO_2-eq in 100 years in the soil are stored:

$$CO_2 - \text{eq} = 57.4 \frac{kg_C}{t_{compost}} * \frac{44 \frac{kg_{CO2}}{kmol}}{12 \frac{kg_C}{kmol}} = 210.3 \frac{kg_{co2-eq}}{t_{compost}} \tag{20}$$

Table 8
Emission factors considered for the calculation of the total emissions in terms of CO_2.

Specific emission factors			
Natural gas combustion	0.259	$kg_{CO2}\ kWh^{-1}$	ISPRA (Caputo, 2017), AECOM 2010
Pellet combustion	0.009	$kg_{CO2}\ kWh^{-1}$	AECOM 2010
Average value considered for the use of electricity	0.544	$kg_{CO2}\ kWh^{-1}$	ISPRA (Caputo, 2017)
Gasoil	3.17	$kg_{CO2}\ kg^{-1}$	APAT, ISPRA (Contaldi and Ilacqua, 2003)

Over 15 years, the total amount of compost produced every 12 months from the analyzed CHRS is approximately 91.1 t, hence the amount of organic carbon stored in the soil over 100 years in terms of CO_2-eq will be 19.2 $t_{CO2\text{-}eq}$ corresponding to 24.9 $kg_{CO2\text{-}eq}\ m^{-3}$ of biomass used to fed the system for a total amount of 770 m^3 of chipped biomass used inside the plant (considering to change the biomass every 24 months). This means that with respect to the total amount of energy provided through the CHRS, the amount of carbon that can be stored in soil for over 100 years is 0,05 $kg_{CO2\text{-}eq}\ kWh^{-1}$.

Adding one CHRS to the real case to provide a total amount of energy of 50,000 kWh y^{-1} only through CHRS and just the remaining 19,840 kWh y^{-1} with a pellet combustor (Case I) promoted the storage of carbon in the soil over 100 years of up to 38.3 $t_{CO2\text{-}eq.}$

The CO_2-eq that can be stored in soil is represented in Fig. 3 and includes the tons of CO_2-eq emitted over the entire operative lifetime of the different scenarios. If the carbon was emitted the values is expressed as a negative value of the CO_2-eq. Therefore, the values in Fig. 3 do represent an estimation of the amount of CO_2-eq that is not released into the atmosphere over 100 years.

Moreover it is possible to have an estimation of the CO_2 saved, that are avoided emissions of fossil CO_2 equivalents (i.e., not released into the atmosphere) using the different technologies. For each one of the eight scenarios, the direct emissions in terms of $t_{CO2\text{-}eq}$ related to the operative lifetime of 15 years were calculated using the appropriate emission factors found in the literature (reported in Table 8).

The calculated CO_2 total emissions were then compared in order to estimate how much CO_2 is saved over this period of time thanks to the implementation of the CHRS instead of other systems.

For the CHRS, the total amount of emissions are mainly due to the leachate recirculation pump that works mainly during the first 15 days of the plant operation each year, to recirculate the produced leachate inside the CHRS. Over the 15-year period, the plant needs to be rebuilt 14 times and the material needed to be chipped using of a chipper machine that contributed to CO_2 emissions. The total emissions calculated for one CHRS over 15 years providing 24,090 kWh y^{-1} was 0.76 $t_{CO2\text{-}eq}$, for two CHRSs providing 24,090 kWh y^{-1} each resulted in a total amount of 1.49 $t_{CO2\text{-}eq}$.

In regards to the solar thermal panels, there were no global warming emissions associated with generating electricity from solar energy which is why Case B turned out to be the less impacting in terms of CO_2-eq emissions. If the entire life of these plants is considered, there are important emissions associated with other stages of the solar panels life cycle, especially in terms of manufacturing, materials transportation, and dismantling. Considering just the operative time, the total amount of CO_2-eq for solar thermal panels over 15 years is equal to zero.

For the geothermal plant, the total amount of CO_2-eq emissions is related to the energy required by the compressor of the plant. A coefficient of performance of 4 was assumed. The total amount of CO_2-eq produced by the geothermal plant over 15 years providing 24,090 kWh y^{-1}, resulted to be more than 49.14 $t_{CO2\text{-}eq}$.

For the pellet combustor and the natural-gas condensing boiler, the combustion process is responsible for the primary fraction of the total emissions of CO_2, calculated through the use of the emission factors reported in Table 8 and multiplied for the kWh provided by the system. For the pellet combustor the emissions related to the transport of the pellets during the operation time were considered, assuming an average distance to be travelled of 10 km and with a gasoil van able to transport a pallet of pellets of about 70 bags (i.e., average number of bags per pallet) consuming one liter of gasoil per kilometer travelled.

The total amount of CO_2-eq emissions of the pellet combustor over 15 years providing 45,750 kWh y^{-1} (Cases B and C) resulted to be more than 6.51 $t_{CO2\text{-}eq}$, providing 69,840 kWh y^{-1} resulted to be almost 10 $t_{CO2\text{-}eq}$ and providing 19,840 kWh y^{-1} (Case I) resulted around 3 $t_{CO2\text{-}eq}$.

The total amount of CO_2-eq emissions of the condensing natural gas boiler in 15 years providing 45,750 kWh y^{-1} (Cases D, E, and H) resulted to be 177.51 $t_{CO2\text{-}eq}$ and providing 69,840 kWh y^{-1} (case G) resulted to be almost 271 $t_{CO2\text{-}eq}$

As shown in Fig. 3, Case G (total amount of energy provided through the use a natural gas condensing boiler) turned out to be the worst solution in terms of CO_2 emissions. The similar observation was made for the other alternative scenarios including the production of energy through a natural gas condensing boiler (Case H, E, and D).

In Table 9, the total emissions in $t_{CO2\text{-}eq}$ and the unit emissions in $kg_{CO2\text{-}eq}$ kWh^{-1} for each scenario are reported, calculated for the operative lifetime of 15 years. In each scenario, the total amount of energy of 69,840 kWh y^{-1} is provided.

Starting from the assumption that Case B considers no emissions at all related to solar thermal panels (not realistic) with a total amount of CO_2 emissions in 15 years equal to 6.51 $t_{CO2\text{-}eq}$ due just to the use of Pellet Combustor, the real case (Case A) turned out to be convenient even in terms of CO_2 emitted (7.28 $t_{CO2\text{-}eq}$ in 15 years). Therefore, implementing the real Case A allows to save up to almost 264 $t_{CO2\text{-}eq}$ in 15 years, respect to the use of one Natural Gas Condensing Boiler, that in terms of $kg_{CO2\text{-}eq}$ kWh^{-1} corresponds to 0.252 $kg_{CO2\text{-}eq}$ saved per kWh of energy provided.

Considering to add another CHRS in the real case A (obtaining Case I, with 2 CHRSs + pellet combustor), resulted the most convenient solution in terms of CO_2-eq emissions. Indeed, the total emissions produced in one year with a Pellet Combustor resulted equal to almost 189 $kg_{CO2\text{-}eq}$, with a total production for the entire Case I (2 CHRSs + 1 pellet combustor) of 4,3 $t_{CO2\text{-}eq}$ in 15 years, even lower than case B, almost halving the emissions respect to the real Case A. Adding a CHRS plant to the real case to cover more than the half part of the required energy with these systems, allows to save 3 $t_{CO2\text{-}eq}$ in 15 years, equal to 0.003 $kg_{CO2\text{-}eq}$ per kWh of energy provided.

3.4. *Economic and environmental affordability*

Valorization of residual biomass from agro-forestry activities by heat recovery and compost production through a CHRS, could be a good solution in terms of both cost and CO_2 savings. This can be clearly seen from Table 5 and Table 9 resuming costs and carbon emissions calculated for the nine scenarios providing the same amount of energy (69,840 kWh y^{-1})

Case A (real case - one CHRS and one pellet combustor) and Case I (2 CHRSs and one pellet combustor) were found to provide sufficient energy for DHW and UHS at competitive prices of 0.087 € kWh^{-1} and 0,074 € kWh^{-1}, respectively, especially in respect to the cases involving the implementation of a geothermal plant (Cases C and E), where the unit prices were 0.120 € kWh^{-1} and 0.124 € kWh^{-1}, respectively (Case E included the use of a condensing natural gas boiler). Hence, even if the geothermal plant is convenient in terms of CO_2 emissions, it is very expensive with respect to the other considered alternatives. Moreover, it is interesting to note that, considering only the green technologies used for comparison (Compost Heat Recovery System, solar thermal panels and geothermal plant), much lower costs are related to the materials involved with the construction of a CHRS respect to the other two green technologies. Indeed, the cases A, B and C involving CHRS, solar thermal

Table 9

Air emissions in terms of $CO_{2\text{-}eq}$ related to the implementation of the different plants, calculated for each scenario considering the operative time, lasting 15 years. (CHRS=Compost Heat recovery System, PC=Pellet Combustor, STP=Solar Thermal Panels, GTP=Geothermal Plant, NGCB=Natural-Gas Condensing Boiler).

SCENARIOS	Case A (REAL CASE) CHRS 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}		Case B STP 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}		Case C GTP 24,090 kWh y^{-1} + PC 45,750 kWh y^{-1}		Case D STP 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}		Case E GTP 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}		Case F PC 69,840 kWh y^{-1}	Case G NGCB 69,840 kWh y^{-1}	Case H CHRS 24,090 kWh y^{-1} + NGCB 45,750 kWh y^{-1}		Case I 2 CHRSs 50,000 kWh y^{-1} + PC 19,840 kWh y^{-1}	
	CHRS	PC	STP	PC	GTP	PC	STP	NGCB	GTP	NGCB	PC	NGCB	CHRS	NGCB	CHRSs	PC
CO_2 EMISSIONS FOR EACH SYSTEM in 15 years ($t_{CO2\text{-}eq}$)	0.76	6.51	0	6.51	49.14	6.51	0	177,5	49.14	177.5			0.76	177.5	1.49	2.83
TOTAL CO_2 EMISSIONS ($t_{CO2\text{-}eq}$) in 15 Years	7.28		6.51		55.66		177.51		226.65		9.95	270.98	178.27		4,32	
UNIT CO_2 EMISSIONS (kgCO2 kWh^{-1}) in 15 Years	0.007		0.006		0.053		0.169		0.216		0.009	0.259	0.17		0.004	

panels and geothermal plant respectively, each of which combined with a Pellet Combustor, showed that cases B and C require much higher initial costs, that are made on the sum of design cost, installation cost and materials cost. For the Case A the total initial costs are 13,130 €, for the case B 30,190 € and for the Case C 50,895 €. This is an aspect that can limit a lot the user's choice to install a green technology respect to a traditional one. CHRS allows to decrease a lot the initial costs a user has to meet when installing a new green technology.

Regarding the CO_2 emissions to the atmosphere solely during the operative phase, it turned out that the implementation of a CHRS coupled with a pellet combustor instead of implementing a natural-gas condensing boiler, promoted a saving of up to 0.252 $kg_{CO2\text{-}eq}$ per kWh of energy provided for a total amount of CO_2 saved in 15 years which is equal to almost 264 $t_{CO2\text{-}eq.}$ Concerning the carbon balance, the implementation of one CHRS working for 15 years, promoted the storage of carbon in the soil over 100 years of about 0.05 $kg_{CO2\text{-}eq}$ per kWh of energy provided for a total amount of CO_2-eq storable in the equal to 19.6 t $kg_{CO2\text{-}eq.}$ This amount doubles with two CHRSs.

The accelerating rates of climate change are considered to have potential influence on ecosystems functioning including organic carbon storage in soil (Li et al., 2020). Land use change causes perturbation of the ecosystem and can influence carbon stock and flown, especially organic carbon storage in soil Lal (2005). The depletion of soil organic carbon stock is attributed to numerous factors, including the decrease of biomass returned to the soil Lal (2005) and the application of biosolids such as compost to the soil offers an opportunity for soil carbon sequestration (Harrison et al., 1995). Preserving and promoting organic carbon storage in soil is considered as a potentially effective strategy to mitigate global climate change (Li et al., 2020). This study showed that the use of CHRSs allowed to reduce atmospheric emissions while improving soil properties through the storage of carbon in soil thanks to the production of compost; therefore, it can be considered a technology that offers the opportunity to produce energy while improving carbon sequestration, enhancing the climate change mitigation.

Moreover, transition to a circular economy requires improvement in both environmental and economic performances of renewable energy systems within the context of sustainable energy and climate change mitigation (Kosmadakis et al., 2021). Stabilizing the atmospheric concentration of anthropogenic GHGs will require decarbonization of the global economy during the next century and this goal implies massive expansion of renewable, CO_2-free sources of energy and renewable energy need to play a significant role in our future at a reasonable cost; this depend on continued technology progress (Arent et al., 2011). This study demonstrated that the use of CHRSs allow to produce sustainable domestic thermal energy at a reasonable cost. Equitable, sustainable and livable societies should use the materials embedded in waste's flows and should be based on the production of energy from these resources (D'Adamo et al., 2021). Authors demonstrated that the CHRS could represent an alternative viable solution for sustainable and economic energy production from waste sources.

4. Conclusions

The present work compared different scenarios for providing the same amount of thermal energy to a Farmhouse. It included an innovative system (CHRS), two green technologies (solar thermal panels and geothermal plant) and two traditional technologies (pellet combustor and natural-gas condensing boiler).Considering both the economic and environmental aspects in terms of CO_2 emissions, implementing a CHRS turned out to be the best solution and was also even better when considering the implementation of two CHRSs to cover more than half of the total amount of energy needs of the farmhouse. In according with the main findings of this research, it is possible to affirm that the CHRS has great potential to furnish renewable heat at competitive prices, while providing other ecosystem services such as carbon storage and nutrients cycling to soil, being also a solution that could serve as an incentive for farmers towards the introduction of agroforestry practices and landscape features.

Based on the objective of optimizing waste management strategies, with a particular focus on resource conservation and climate protection, the process of energy recovery using a CHRS and biomass recycling should be considered in the future as a complementary system to cover at least 50% of the energy need for a building, as required by national policies.

Authors contribution

Pivato A., Schievano A. and Malesani R. conceptualized the study design; Muraro S. contributed to build the plant and provided the main data about the economic aspects of the plants. Schievano A. and Bocchi S. performed the laboratory tests about the degradation performances; Malesani R., Pivato A. and Schievano A. developed the methodology, collect the main data and performed the analysis and calculations to compare the scenarios. All authors collaborated to the results interpretation; all authors wrote, read, commented and approved the final manuscript .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.envc.2021.100131.

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