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Research to Industry and Industry to Research

COMPOST HEAT RECOVERY SYSTEMS – A TOOL TO PROMOTE RENEWABLE ENERGY AND AGRO-ECOLOGICAL PRACTICES

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A recent ENEA Report focussing on the environmental impacts of combustion highlighted how, in recent years, the sector that has contributed most significantly to a worsening of air quality in Italy is that of domestic heating. Indeed, despite the improvements in technology performance, an increase in particulate matter emissions (both PM_{10} and $PM_{2.5}$) has been registered, mainly caused by increased biomass combustion (ENEA, 2017). Compost Heat Recovery Systems (CHRS) are alternative plants for domestic heating that allow the recovery and sustainable use of thermal energy produced during the aerobic biodegradation of biomass waste originating from urban gardening/pruning residues and agricultural/forestry activities. These are plants fed with organic residues, but no combustion processes are involved, thereby avoiding PM emissions associated with heat production. The process involved is the aerobic biodegradation (aka composting process), capable of releasing considerable heat and reaching temperatures of up to 65-70°C. The heat released is recovered by thermal exchangers and used for domestic purposes. Moreover, the more recalcitrant fractions of organic matter that are not readily hydrolysable and therefore not available for microbial oxidation, remain in the compost, which is subsequently returned to the soil. By this means, CHRS are not only sustainable, but also regenerative for the environment. They indeed have the potential to mitigate climate change and achieve a carbon-negative balance once a considerable fraction of the carbon fixed by plants during photosynthesis has been stored in soils as compost and contributed to long-term soil carbon pools. The possibility of storing carbon in soil is an important aspect of CHRS particularly as, according to the Italian Institute for the Environment Protection and Research, approximately 80% of Italian soils feature an organic carbon content lower than 2% (ISPRA, 2008).

Figure 1 shows a conceptual model of the plant.

CHRS provides sustainable energy whilst also yielding effective waste management solutions, thus fully implementing the principles of circular economy with low-profile organic residues and waste being fully valorized and finally returned to the soil. Concomitantly however, the requirements of the blue economy are also met. Gunter Pauli

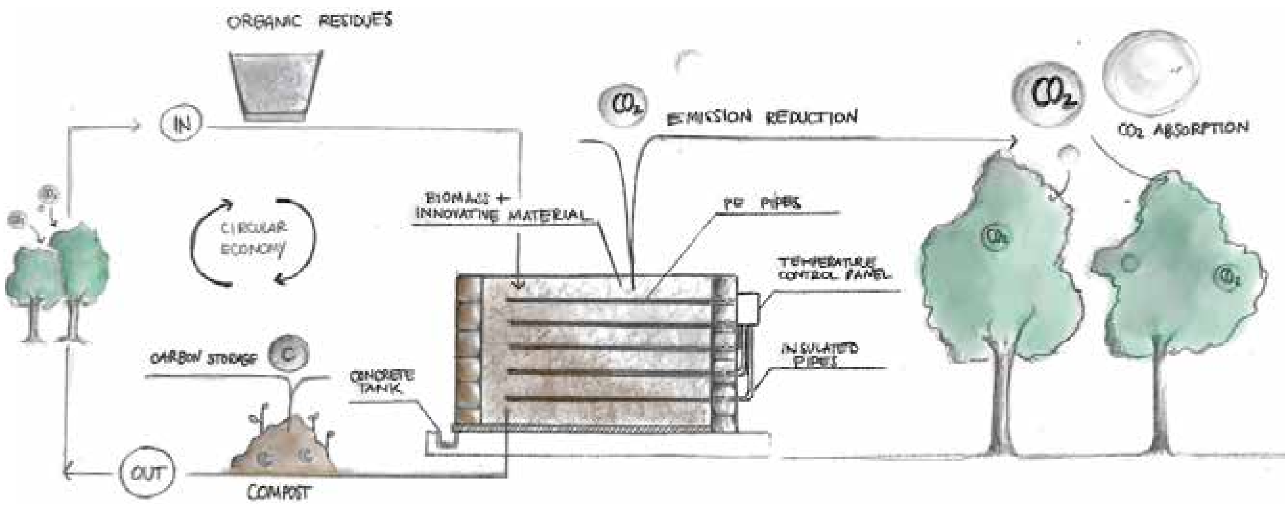

FIGURE 1: Conceptual model of CHRS showing carbon dioxide removal rates, compost production and valorization of organic residues.

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(2010), the founder of the blue economy concept, has underlined how the time has come for societies to move to a pragmatic redesign of the economic system inspired by ecosystems, using locally available resources and transforming one person's waste into another's resource. CHRS comply with these biomimetic principles, which merely improve on a function which occurs naturally in ecosystems to revalorize local residues and regenerate the environment.

1. State of the art of different technologies

Extensive literature reports have been published with regard to well-established composting processes, whilst the literature relating to heat generation and recovery from composting is disjointed and incomplete. This is largely due to the fact that heat recovery from composting processes is frequently achieved on the basis of independent projects conducted by researchers or enterprises in their search for inexpensive energy systems (Zantedeschi, 2018). Rural farmers in ancient China first captured this form of renewable heat over 2000 years ago with the use of hotbeds (Brown, 2014). However, it was only in the 1960s that Jean Pain set up experiments to investigate how this form of heat could be used to heat buildings (Zimmermann, 2020). From the advent of Jean Pain's studies to the 1990s, systems for use in the recovery of energy from composting evolved from conduction-based recovery systems to those using compost vapor stream to capture the latent heat. Accordingly, numerous different configurations have been adhered to worldwide in recovering heat produced during composting processes and exploiting it for the heating of buildings. Four different CHRS configurations are reported and compared below. The main differences relate to the way in which heat exchange is carried out. A comparative analysis between the configurations considered is provided in Table 1.

- Traditional CHRS consists essentially in a heap of raw biomass placed inside a cylindrical container system made of welded iron mesh. The system is insulated with a waterproof membrane and the cylinder surrounded by hay bales; a waterproof bottom membrane allows the leachate produced to be collected and conveyed to a concrete well housing a leachate recirculation pump. 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, https://native-power.de/). The heat generated is recovered by means of spirally-arranged polyethylene pipes fixed on wire mesh at different heights inside the cylinder inside which an exchange fluid flows. Oxygen required by microorganisms is provided using perforated polyvinylchloride pipes placed vertically inside the cylinder promoting aeration by means of a chimney effect (statically). An illustration of the plant scheme is provided in Figure 2.
- The Biologik^R technology differs from traditional CHRS with regard to the type of heat exchanger used. Biologik CHRS does not use polyethylene pipes but rather a metal exchanger inside the biomass pile. The heat exchanger is placed directly inside the body of the plant, reducing heat dispersion and enhancing efficiency of the plant. The related costs are on average much higher than those of a traditional system, due to the presence of the large heat exchanger. The external structure of these systems is comprised of a double iron welded mesh layer inside which homogenously-sized stones are placed for insulation and to allow oxygen to flow statically throughout the body of the plant. The plant is based on a grid base containing gravel and one side of the plant comprises a wood closing wall. Figure 3 provides an illustration of the Biologik CHRS.
- The Condenser Type CHRS facilitates recovery of latent heat by means of vapor condensation. Since the majority of heat released during composting is contained in the latent form of water vapor (Bajiko et al., 2019), to improve the rate of heat recovery a heat exchanger based on condensation of compost vapors may be used. This solution overcomes the problem

TABLE 1: Characteristics and differences between different configurations of CHRS.

Configuration	Feeding material	Process	Aeration system	Insulating system	Heat recovery	Latent heat recovery	Material output	Energy output	References
Traditional CHRS	Woodchip	aerobic	static	Waterproof membrane + hay bales	Polyethylene pipes + exchange fluid	No	compost	Thermal energy	Pain and Pain, 1985 Native Power (https://native-power.de/en/) Biomeiler (https://www.biomeiler.at) associations
Biologik^R	woodchip	aerobic	static	stones	Metal heat exchanger placed inside	No	compost	Thermal energy	Biologik Association (http://www.biologik.it/)
Condenser type	Woodchip, grass, manure	aerobic	static or forced	Waterproof membrane + Hay bales	Low Density Polyethylene pipes + exchange fluid	Yes	compost	Thermal energy	Bajiko et al., 2019
Micro-bioenergy	Woodchip, manure, food waste	hybrid (aerobic + anaerobic)	static	Waterproof membrane + Hay bales	Polyethylene pipes + exchange fluid	No	Compost + digestate	Thermal energy + biogas	Zantedeschi, 2018

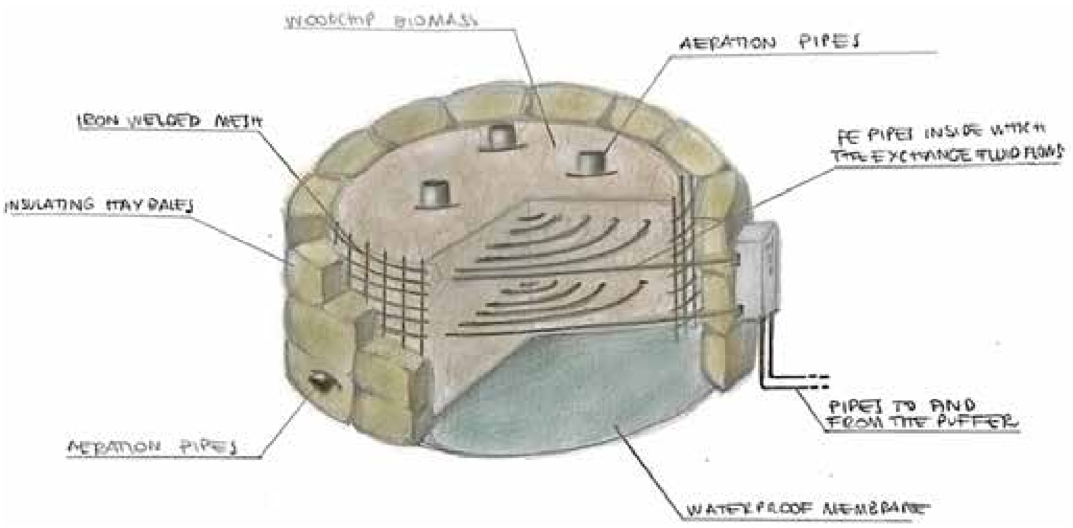

FIGURE 2: Illustration of a traditional CHRS.

of direct heat removal from internal parts of the compost pile that may affect microorganism activity and enhances recovery of the latent heat bound in the liquid-vapor phase. The captured heat is transferred using a heat-carrying medium and the condensed water reused to maintain optimal moisture conditions inside the plant. The heat exchanger is placed on the top of the plant at the end of construction and does not affect the dismantling process. The hot vapor reaches the top by means of natural convection in passively aerated piles, thus highlighting the importance of intensifying the chimney effect. The heat exchanger is made up of Low Density Polyethylene (LDPE) spirally-arranged pipes.

To promote vapor accumulation and condensation on the heat exchanger surface, a cavity is created under the piping system using a wooden lath structure. The aeration pipes are placed vertically but instead of turning up from the top, before the last layer the pipes are folded to exit sideways. A layer of mature compost is placed on top of the plant to act as a biofilter. Figure 4 provides an illustration of a Condenser Type CHRS.

- Microbioenergy involves the installation of an anaerobic digester (micro-biogas plant) inside a traditional CHRS. As anaerobic digestion is an endothermic process, in this configuration, the function of the CHRS is to keep the digester warm whilst providing thermal energy to a building. Microbioenergy yields compost, ther-

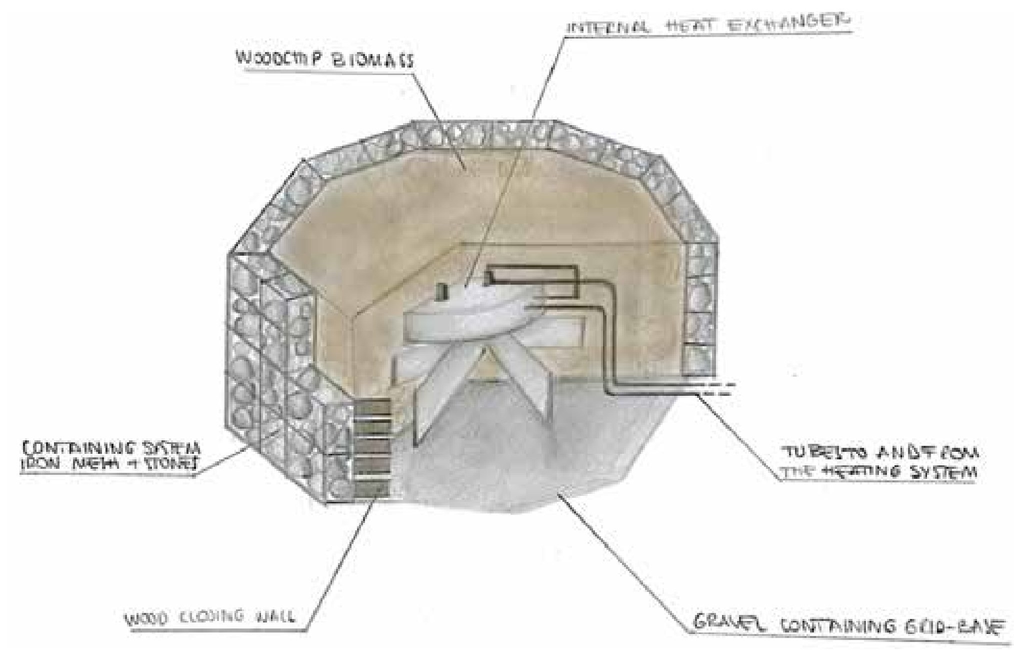

FIGURE 3: Illustration of Biologik CHRS.

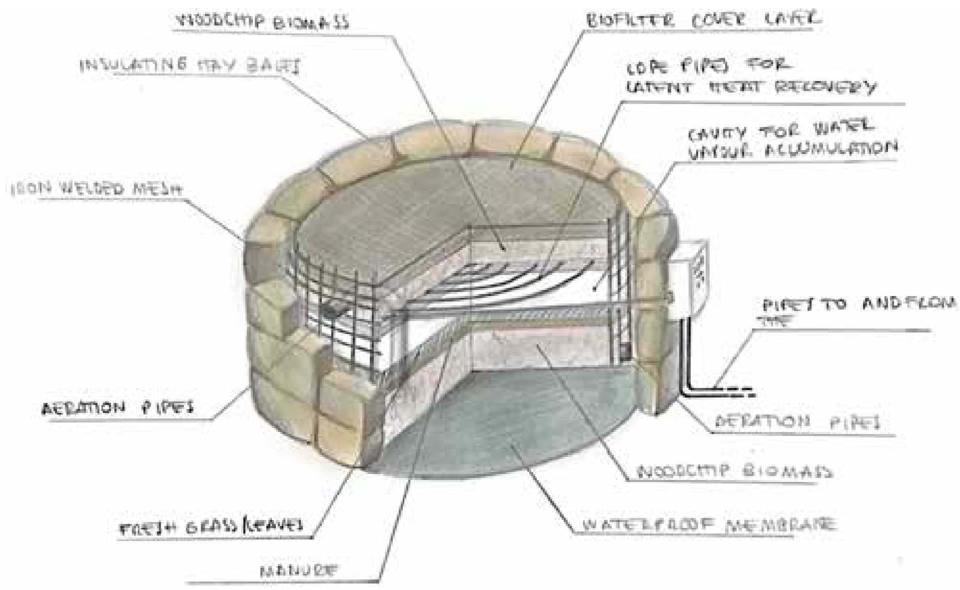

FIGURE 4: Illustration of a condenser type CHRS.

mal energy and biogas. The aerobic part of the plant is fed with woody biomass while the anaerobic part is fed with readily biodegradable organic material (manure and food waste). The dimensions of traditional CHRS and the digester vary and do not feature a linear proportion; generally, CHRS volume is in the classic range of 35 - 55 m^3. Heat is recovered through the traditional polyethylene pipe system. Simultaneously, methane is produced and collected through a biogas outlet pipe in a dedicated tank, compressed and used after desulfurization for many different purposes, including powering a stove or a gas-fueled boiler to produce hot water or sent to a co-generator to produce electric energy.

By means of this configuration both compost and digestate are produced; compost is used directly while the digestate is treated and used in various ways; it may be collected in a septic tank, aged, separated and dried to be used as fertilizer. An illustration of this system is provided in Figure 5.

All these plants are generally connected to a puffer by means of which the recovered heat is distributed between the Underfloor Heating System (UHS) and the Domestic Hot Water (DHW) system of a building. The biomass that undergoes biodegradation in the CHRS is capable of providing adequate levels of thermal energy for approximately one year. After this period, the thermal energy yielded is no longer sufficient and the biomass should be replaced. For this reason, once a year CHRS should be dismantled and rebuilt using new chipped biomass.

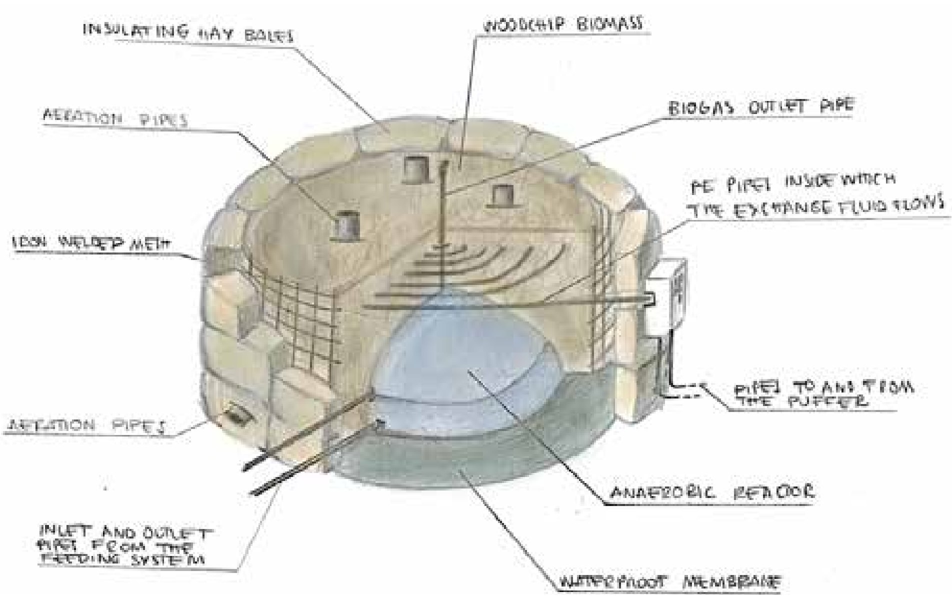

FIGURE 5: Illustration of a Microbioenergy CHRS.

2. Current research activities for the development of CHRS

CHRS is in a position to compete on the market with both traditional and green technologies such as pellet combustor or natural gas condensing boilers and solar thermal panels or geothermal plants, respectively. CHRS features two main advantages over competitors: low investment costs and potentially lower GHG emission balance. On the contrary, the main limitations relate to a need for maintenance (typically once yearly) and high volumes/spaces occupied by the heaps. In order to maximize the advantages and reduce limitations, further research should be conducted to address the following topics:

- Evaluation of CHRS emissions related to the full life cycle by means of a Life Cycle Assessment study.
  CHRS should be compared to other technologies from both economic and environmental viewpoints. Environmental assessment will take into account not only operational life span of the system, but also full life cycle of a CHRS using LCA. Moreover, the potential impact of unwanted emissions on overall carbon balance should be considered. Locally-established anaerobic conditions in 'dead-zones' of the heap might lead to release of considerable amounts of methane; emissions of nitrous oxide and ammonia from nitrogen-rich biomass should also be evaluated.

- Evaluation of thermal power output through monitoring of a real-scale CHRS.
  Information relating to the thermal power output of CHRS is based on literature data suggesting an average value of 0.1 kW/m^3 of biomass, depending on different parameters. According to the Native Power association, a traditional plant (volume ranging from 25 to 80 m^3) fed with chipped woody biomass yields an average thermal power output of approx. 0.05 kW/m^3 of biomass. These data reveal how thermal power output is predominantly linked to the dimensions of the plant and the material used to feed the plant. In order to determine more accurate output values, traditional plants should be regulated by means of innovative remote monitoring systems purpose designed for CHRS. These consist in a Wi-Fi control unit connected to measurement probes capable of storing plant functionality parameters on a graphical interface. The objective is to test this innovative device and optimize the same by adding new monitoring probes for the measurement of additional parameters.

- Optimization of plant configuration and thermal energy production processes.
  Currently, CHRS are not a viable solution for use in contexts with low space availability, and have a limited operational life span due to degradation of the biomass; after 12-14 months the plant will need to be dismantled and rebuilt using new biomass. These aspects limit the potential field of installation of a CHRS and increase the costs. Studies are currently being carried out to investigate ways of overcoming these limitations. Potential future developments are represented by the use of innovative support materials featuring electrochemical properties. Use of these materials will be combined with new organic readily biodegradable substrates, implying the installation of an external feeding system and determining a new configuration that could reduce the volumes involved and prolong the operational life span of a plant.

- Implementation of CHRS to boost ecosystem services.
  CHRS are currently being considered for use in the context of Agroforestry (AF) systems, i.e. systems adopted to provide a series of different ecosystem services, including biodiversity enhancement, carbon sequestration, nutrient retention, and soil water retention, whilst maintaining high cash-crop yields (Beillouin et al., 2019). To demonstrate the ability of CHRS to function synergistically with AF systems providing agro-energy by 'intercepting' the residual biomass to produce bioheat while contributing to soil carbon and nutrients stocks, real scale plants should be implemented and both the plants themselves and the agroforestry system that feeds them closely monitored.

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