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Environmental and Energetic Performance of Crematorium Plants

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In recent years, in Italy, the use of cremation has grown considerably, consequently, the demand for new facilities in the area has also increased. However, the installation of new plants is often hindered by environmental associations who fear the environmental impacts of the crematoria. Scientific memoirs relating to the environmental aspects of this activity are generally intended for specific conferences, regulation also may vary from region to region. It is necessary to exercise transparency and comparison about the polluting emissions of other environmentally relevant activities. The present paper wants to make available a document with a high technical and scientific profile, which provides a methodological framework for assessing the impacts of crematoriums. To support the analysis experimental surveys on pollutant emissions, their local impact and compliance with current regulations are reported. In addition, the memorandum presents a feasibility project for the crematorium temple of Gemona del Friuli (Udine - Italy). The project wants to achieve two energy and environmental objectives, based on the thermal recovery of the energies generated by the combustion of the wooden coffin and the used fuel, aiming at the minimization of the impact. The first target is to make the crematorium independent from external energy networks (off-grid), while the second is to supply a district heating service for some users operating at short distances (i.e., two schools, a gym, and a swimming pool). From the environmental point of view, we reduce the carbon footprint of the activity and harmful emissions.

1. Introduction

In 2020, 87 cremation plants were authorized in Italy and operated with 247,840 cremations of corpses (194,669 in 2019). In addition, there are 29,266 cremations of mortal remains (compared to 38,305 in 2019) (SEFIT, 2020). The average cremation per facility in 2020 was 2,849 (2,290 in 2019), so a total of 3,185 cremation/crematoriums for 2020 is reached. The construction of cremation plants is often opposed by the local population due to the well-known NIMBY (i.e., “Not In My Back Yard”) phenomenon. Furthermore, the regional regulations have created particularly heavy legislative barriers that have further burdened the construction, going against the trend of the guiding principles of the consolidated environmental text D. Lgs. 151/2006.
Hence there is a need for a systematic study with a plant approach on the environmental, energy, global environmental (i.e., CO_2 emissions) and local environmental (i.e., pollutant emissions: mainly NO_x, SO_2, PM) performance of cremation and for the identification and evaluation of the technical efficiency measures to tend to a zero-impact cremation activity. The functional configuration of a generic plant is generally totally dissipative, while the current needs for energy and environmental efficiency lead to the need to focus on recovery activity as well. This paper analyses the energy efficiency potential of the incineration lines and crematory temples equipped with several oxidant combustion cremation lines. The incineration lines, technically and functionally equivalent to each other, operate in parallel. The experiments and evaluations were carried out on a typical crematorium temple consisting of two cremation lines with a daily operational program (Dal Moro and Nardin, 2012) (Basso and Nardin, 2014). The analyses carried out can be applied, with good approximation, to a generic oxidant combustion cremation line, regardless of the technology and installation site, and the evaluations can easily be generalized to a plant configuration with more coupled lines. In the technical and scientific literature,

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at present, there is no systematic approach of the plant type to the environmental and energy sustainability of this activity.

2. Balance of thermal energies and power of a cremation line

Figure 1 presents the scheme for a generic cremation plant. The cremation process (CR) concerns corpses and extumulated remains. In both cases, there is the cremation of one unit at a time, in succession, for the daily operating time. The composition of bodies and remains is linked to contingent management choices. Combustion takes place in two chambers: a primary (combustion) and a secondary (post-combustion). The solid mass (i.e., chipboard coffin, body) is burned in the primary chamber with the aid of fuel (i.e., methane). In the secondary chamber, the gases produced are completely oxidized, again with the aid of fuel (generally methane). In the primary combustion chamber, the temperature is correlated to four main phases, characterized by a different development of the oxidation process: 1 - phase of heating, combustion of the paint and of the top of the coffin; 2 - combustion phase of the entire coffin; 3 - body combustion phase; 4 – phase of calcification, ash formation and cooling (Nardin et al., 2012, 2014). Temperatures also have a very variable trend in the combustion chamber: the temperature rises rapidly due to the combustion of the paint, and after a few minutes it rises further due to the combustion of the wood, reaching the maximum value of about 1,025 °C. All the gases produced in the primary combustion chamber are conveyed to the post-combustion chamber, where the oxidation processes are completed. The combustion products reach a maximum temperature of about 1,110 °C. The specific function of the post-combustion chamber is to obtain total oxidation of the cremation gases, with a temperature that must be kept above the minimum legal limits (≥850 °C) by means of an installed thermoregulated burner at the entrance to the post-combustion chamber (pcc). The average temperature leaving the post-combustion chamber is about 900 °C.

2.1 Energy flows

Figure 1 shows the energy balance of the process using the data of temperature, fuel flows and volume experimentally detected (Nardin and Ciotti 2017). The average weight of a body is 75 kg, of which about 80% is composed of water while 20% of lipids which participate in the combustion that occurs only after the total evaporation of the liquids. The wooden coffin has a weight of about 50 kg. The average consumption of methane is about 25 Sm^3/CR. The average electrical consumption is about 17 kWh_{el}/CR, and the average cremation time is about 75 minutes, so it is necessary to multiply the energies developed by a factor of 0.8 to obtain the hourly thermal power.

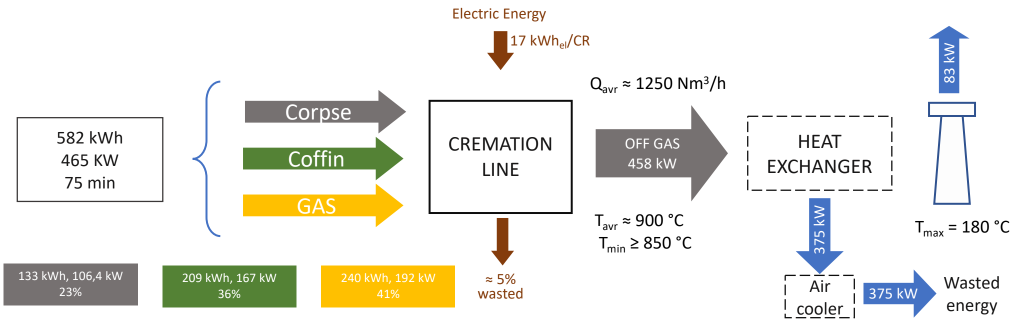

Figure 1: General scheme and balance of energies and thermal powers of a typical cremation plant.

2.2 Current state

All the assessments concern the operational functioning of a single incineration line. In the case of a crematorium made up of several lines operating in parallel, it is sufficient to multiply the values of the parameters considered by the number of operating lines. The economic, energy and environmental assessments are carried out based on the average operating conditions of a typical cremation and on an annual basis considering a regime of 2,000 CR/y per line. Table 1 presents the plant's technical characteristics and operating times.
The economic, energy and environmental assessments (i.e., global CO_2 and local NO_x, SO_2, PM) exclusively concern the procedural activities for cremations with the exclusion of the energy needs of the general services of the crematorium, which in any case are marginal with respect to the process operation. The evaluations refer to the single cremation and to the activity on an annual basis at a nominal regime of 2,000 CR/y. The cremation of remains from extumulation which are occasional and constitute a minimum percentage of the cremation activity, generally around 20%, is excluded from the assessment. The assessments were made based on the emission factors listed in Table 2.

Table 1: Plant technical characteristics

Thermo-technical characteristics		**Operating times**	
Average flow rate of combustion products	1.250 Nmc/h	Time for a typical cremation	75 min
Average temperature of the combustion products entering the pcc	900 °C	Time available daily	12 h
Average thermal power of the combustion products exiting the pcc	458 kW	Average daily preheating time, stand by and setup	2 h
Average temperature of the fumes entering the bag filter	180 °C	Operating time in the presence of the cremation unit	8 h
Dissipated thermal power	83 kW	Days of the year available	300 d/y
Calculated heat output recoverable from an incineration line (8 h)	375 kW	Cremations per year at a medium rate	2.000 CR/y

Table 2: Emission factors (ISPRA 2017) *used to calculate the impacts*

	FCO_2	FNO_x	ESO_2	EPM
Electric energy	545,00 kg/MWh_{el}	421,7 g/MWh_{el}	127,2 g/MWh_{el}	10,17 g/MWh_{el}
Gas boiler	200,88 kg/MWh_f	54,0 g/MWh_f	0,612 g/MWh_f	1,62 g/MWh_f

The analysis carried out (Nardin, Barazzutti, and Ciotti 2021) determined the global impacts of a cremation line at present in terms of costs, consumption of fossil fuels and CO_2 emissions (Figure 2). The assessments made, with acceptable approximations, can be generalized to a generic cremation line.

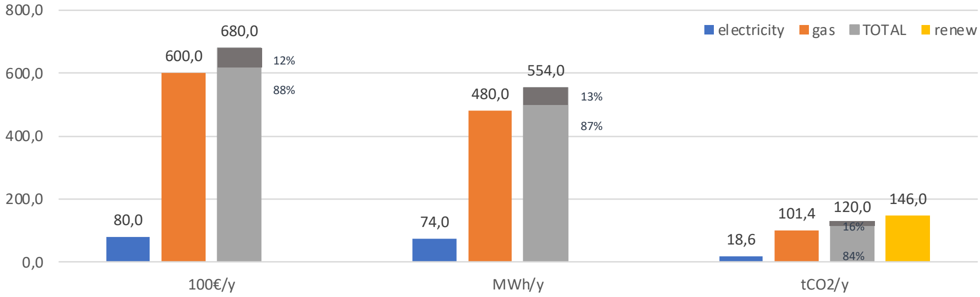

Figure 2: Global impact at the current state. Note: the yellow bar represents the CO_2 from renewable sources not used so far. Values are referred to 2,000 CR/y.

3. Ethical, environmental and energy efficiency

Crematory temples generally dissipate all the energy in the products of combustion. In a few cases, there is a system suitable for the reuse of a small part of the energy produced to heat the offices in the cemetery area. In some cases, in Northern European countries where cremation is widespread, the recovery of thermal energy is used in the immediate vicinity of the cemetery area. The efficiency study intends to reconcile three objectives: moral ethical, environmental, and social. Moral ethics is necessary to avoid improper use of the thermal energies generated by the bodies: the body contributes about 23% to the production of thermal energy, and this amount will be released into the atmosphere without any kind of reuse. Environmental ethics is aimed at decarbonating the environment, reducing the use of fossil sources, and reducing the local environmental impact. The incineration activity must first aim at zero environmental impact, and, subsequently, develop any virtuous effects. Social ethics requires the application of the principles of the circular economy; during incineration, wood and methane contribute to producing thermal energy (for more than 3/4 of the total) currently dissipated. The goal is to apply technologies to recover much of this energy to cover endogenous thermal, refrigeration and electrical needs and/or to provide thermal energy to external users with district heating networks.

4. Energy efficiency technologies

The crematorium temple is, currently, energetically powered directly or indirectly by fossil sources with electricity from the network and methane from the network; this system can be defined as On-Grid. This study, starting from the current state of the technologies of the crematoria with the relative global (i.e., CO_2) and local environmental impacts (i.e., local polluting emissions NO_x, SO_2, PM) and the use of fossil sources, tend to achieve a no impact or virtuous cremation activities. The efficiency options are numerous and in some alternative cases, it is necessary to proceed systematically to highlight and classify them. Furthermore, the efficiency measures must, in any case, meet economic sustainability criteria. The technical options are numerous and technically feasible, but only a few are viable from an economic point of view. Efficiency interventions can be defined into three types: i.e., input, endogenic and output.

5. Input efficiency interventions

The adoption of On-Grid measures is energetically and environmentally burdened by the thermal equivalent of the electricity used, currently set at 2.17 (kWh_{th}/kWh_{el}) (ISPRA 2017). Input interventions tend to reduce the use of fossil sources and act on the structure of energy supplies and can consist of integration with renewable sources: e.g., we can use a photovoltaic system or purchase energy sources certified as green and/or with neutral impact (IGO or biomethane). Other possibilities are the adoption of a cogenerator or an Off-Grid solution with the use of a liquefied natural gas tank combined with a cogenerator/trigenerator in the absence of energy supply networks. This solution could be integrated by an electric accumulator and a district heating network powered by the thermal energy generated by the cogenerator in addition to the thermal recovery from the off-gases. This plant configuration is characterized by a minimum dissipation on the cogenerator of 15 - 20%. The Off-Grid solution is certainly the best performing in terms of minimizing CO_2 emissions. However, due to the small size of the cogenerator, this solution requires relatively high investments that fall within the logic of return in more than 10 years unless important non-repayable loans (Caronia and Nardin 2018) (Nardin and Ciotti 2017). It would be interesting in electric crematory ovens, due to the greater electrical needs and the related heat recovery from the cogenerator.

6. Endogenous efficiencies

The endogenous interventions concern the cremation process and are both of a technical and managerial nature. The technical intervention consists of the dilution of the combustion products with external air: a reduction in the percentage of O_2 in the combustion products currently in the region of 13-14% and moving towards 11%. This decrease in the O_2 percentage reduces the flow rate of the hot fumes expelled into the atmosphere at temperatures of about 200 °C (losses due to sensible heat). A further trick is to use a mixture of external air/recycled fumes enriched with pure oxygen with two advantages: to reduce sensible heat losses and to speed up the incineration process. In the latter opportunity, it is necessary to avoid excessive NO_x production. A more relevant management intervention consists in reducing the non-operating times per day, in which refractories cool down, by extending the operating time of the cremations from the current 10 hours a day to longer times (from 14 h/d to continuous daily operation). The thermal inertia of the refractories reduces the consumption of methane for daily start-ups and the consumption of methane for cremation. Furthermore, the specific times for cremation are reduced by approximately 2 min of reduction for each subsequent cremation (Nardin, Barazzutti, 2021). From experimental surveys, the methane consumption is reduced from 30 m^3 for the first cremation to the sixth with an average reduction of 4 m^3, from one cremation to the next, due to the thermal inertia of the oven; the refractory structures heat up progressively with the progress of the cremations. With this intervention, the methane requirements for thermal support are on average reduced by about 50%, going from about 25 average Sm^3/CR to about 12.5 Sm^3/CR.

7. Output efficiency interventions

The system is equipped with a fabric bag filter, whose functional limit, when fully operational, is a maximum temperature of 200 °C. It is therefore necessary to cool the combustion products that come out of the afterburner chamber to an average temperature of about 900 °C. The fumes cooling section consists of a primary fumes/water heat exchanger complete with an automatic tube bundle cleaning system, air-cooler, circulation pumps, expansion tank, and closed tank type hydraulic connection circuit. The recovery of thermal energy from the fumes by transforming the current heat exchanger with a dissipative function in a heat recovery system with the insertion of a secondary water/water plate-type heat exchanger. The possible recovery configurations are:

- Electric energy recovery through a single ORC system in front of the two cremation lines.
- Cogenerative energy recovery (electric and thermal) through ORC cogeneration and heat recovery.
- Exclusively thermal recovery mainly in district heating (DHL).

It should be noted that the recovery only concerns the energy generated by the coffin and methane except for the thermal energy generated by the body which was evaluated as 23% of the total energy contained in the Off Gases. The thermal recovery solution will be equipped with a system for measuring and controlling the thermal energies dissipated in the fumes and with the air cooler to ensure a dissipation rate of no less than 23%.

7.1 Recovery with an organic Rankine cycle (ORC) turbine

The first two plant configurations involve the use of an ORC turbine. For the thermal power recovered from the cremation lines (250 kW/line), the electrical yields are of limited value, around 8-10%. For a crematory temple consisting of two cremation lines, we have about 500 kW_{th} in input with an output power of about 48 kW_{el} and a nominal power of 50 kW_{el} with a unit price of 4.5 - 5 k€/kW_{el} and an estimated total price of 250 k€ which strongly penalizes the economic feasibility. In addition, to become the ORC's power supply recuperator, the current heatsinks will have to provide a superheated water temperature of about 120 °C instead of the current hot water temperature of about 95 °C maximum. It is therefore not suitable for supplying overheated water and must therefore be replaced with a new exchanger, weighing down the investments and bringing them to no less than 300 k€. The electricity produced summarily evaluated is equal to 120 MWh (i.e., 3,000 h * 40 kW). Assuming total self-consumption of the electricity produced within the crematorium and an average price of 300 €/MWh, we have a total saving of about 36 k€/y; even considering efficiency certificates, the revenues do not exceed 40 k€/y. The gap between the planned investment for the ORC machine and the new exchanger and the annual cash flows leads to the unfeasibility of this intervention, even in the cogenerative and regenerative configuration and in the High-Efficiency Cogeneration regime. The investment becomes interesting in the case of a crematory temple consisting of 4 cremation lines, and an input power of about 1 MW_{th} from which about 100 kW_{el} can be produced with a specific cost of the ORC around 2.8 k€/kW_{el}. In this case, it is advisable to carry out detailed assessments in a cogenerate/trigenerative configuration in the presence of thermal/refrigeration users.

7.2 Exclusively thermal recovery

Considering the marginal thermal needs of the crematorium, the heat recovery will concern a plurality of nearby external users powered by a district heating network. Heat recovery is a relatively simple technical solution as the temperature of use is lower than the boiling temperature (below 100 °C) which allows the current flue/hot water exchangers to be used without technical modifications. The technical and economic feasibility is strongly influenced by the length of the distribution backbone of the DHL.

8. District heating network case study

The case study concerns the Gemona del Friuli (Udine, Italy) crematorium temple, consisting of two cremation lines, from which heat recovery is carried out to power a series of users with a DHL network (Figure 3).

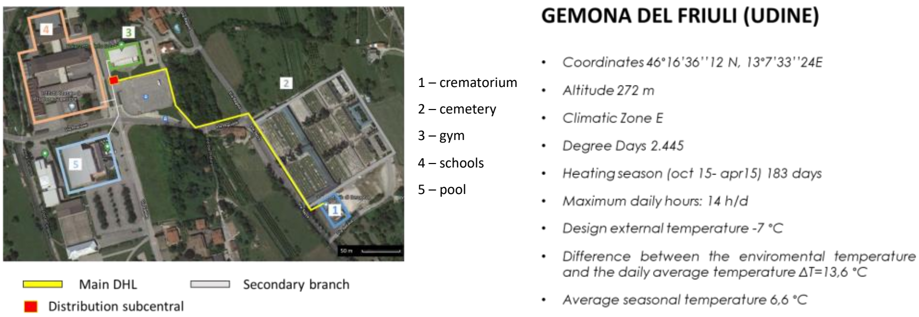

Figure 3: Interested area map with a possible network, and the area climatic characterization.

There are four district heating users from the crematorium temple, the nominal powers and winter thermal requirements are shown in Table 3. Figure 4 shows the duration curve of the total thermal needs; the figure shows the thermal power of 500 kW_{th} recovered from the crematorium temple distributed over 12-14 h/d. The duration curve shows graphically that the power recovered from the crematorium temple is almost totally absorbed in the winter heating season. The total methane requirement of the swimming pool in the summer season of 2018 is equal to 29,388 Sm3 which can be entirely covered by the heat recovery from the Crematorium Temple: the maximum necessary thermal powers are approximately 350 kW compared to the 500 kW available. Considering the seasonal performance of the natural gas boiler, the energy requirement of the pool water is 240 MWh/y. The total annual thermal energy recovered from the crematorium temple is approximately 1,240 MWh/y equal to approximately 83% of the total energy made available by the crematorium temple recovery.

Table 3: Nominal powers and thermal requirements in the winter season.

Utility	Estimated thermal power [kW]	Total seasonal heat requirements [kWh]
School 1	500	918.810 (44%)
School 1	283	548.865 (26%)
Gym	293	176.650 (8%)
Pools	1.015	449.055 (22%)
TOTAL	2.091	2.093.380

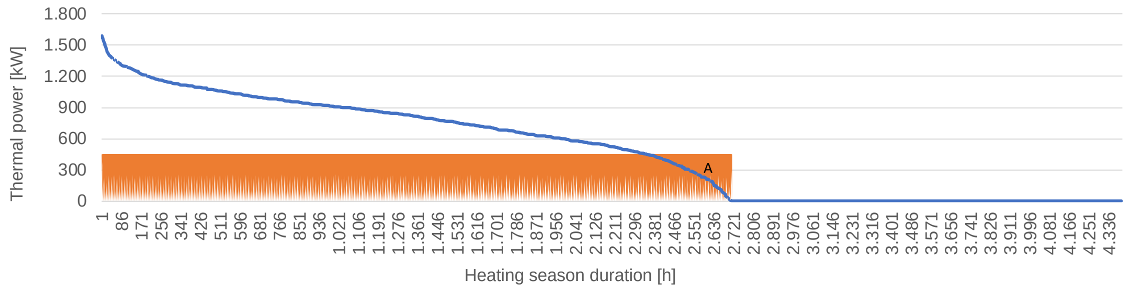

Figure 4: Coverage of recovered energies (orange) compared to the needs (blue).

9. Conclusions

The memoir reports a project to improve the efficiency of a specific crematorium temple with substantially zero environmental, energy and economic impact. The research carried out a systematic study of the technical and managerial measures to increase environmental, energy and economic sustainability to aim at a zero impact and possibly a virtuous effect on the territory. Some technical solutions concerning the production of electricity or cogeneration/trigeneration have proved to be too onerous because of the small size of the machines. The most performing solution was the thermal recovery to power a series of nearby thermal users connected through a DHL network. However, the proposed solution operates a dissipation of about 28% of the thermal energy contained in the off-gases higher than the ones produced by the body equal to 23%. Due to the constant performance of the incineration line, independent of the technology, the assessments made can be generalized to a crematorium regardless of the installation site in the presence of nearby thermal users. The results of the assessments of the global impacts are shown in the histogram in Figure 5a. The project can be defined as totally green as the recovered thermal energy derives exclusively from the avoided heat dissipation. The overall balance between the "impact" and the "virtuosity" leads to a cancellation of the impacts and to a residual virtuosity that contributes to a small extent to the decarbonisation and reduction of fossil fuels at a territorial level (Figure 5b). The incoming cash flows will amortize the investments necessary for the realization of the thermal recovery; the assessments carried out lead to a payback time of approximately 3 years. The projected efficiency also has a social value as it involves a 15 -20% reduction in the energy bill for the heating service of users.

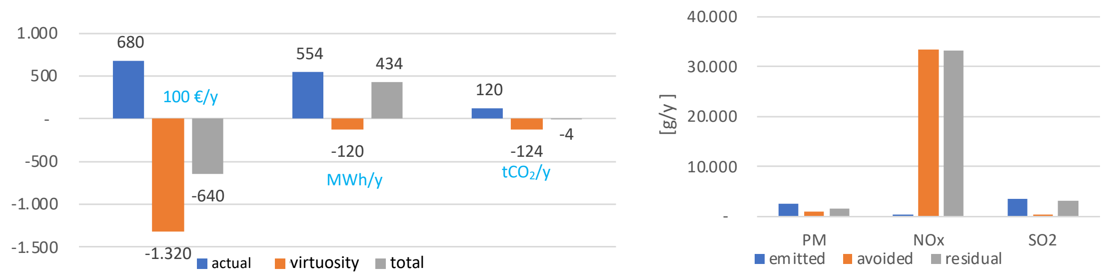

Figure 5: (a) Overall technical impact: for energy bills (€/y), energy consumption (MWh/y) and CO2 emissions (tCO2/y); (b) local virtuosity in terms of PM in the Off Gas, NO_x and SO_2. Values are referred to 2,000 CR/y.

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