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Combined heat and power production based on sewage sludge gasification: An energy-efficient solution for wastewater treatment plants

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ABSTRACT

The main operating costs of wastewater treatment plants are related to the energy consumption and the disposal of by-products. Energy recovery from sewage sludge may be a solution to face both these challenges, improving the sustainability of wastewater treatment plants and making them an example of a circular economy. In this work, the energy and economic analysis of an integrated combined heat and power system based on sewage sludge gasification is proposed. The whole process is simulated by using the commercial software Aspen Plus®. A restricted equilibrium model is used to simulate the gasification of sewage sludge in an atmospheric fluidized bed reactor using air as a gasification agent. Syngas produced from gasification is used as a fuel in an internal combustion engine for combined heat and power production. Different solutions are compared: the internal combustion engine is supposed to be fuelled with syngas or with syngas and methane. In line with the pertinent literature on integrated biomass gasification–internal combustion engine systems, the engine is modeled by combining a compressor, a combustor and a turbine to simulate the four thermodynamic steps of an internal combustion engine. Electric and thermal energy produced by the system is used to supply a fraction of the demand for wastewater and sludge treatment. The energy analysis is carried out for a real wastewater treatment plant that serves 1.2 million of population equivalent, located in Southern Italy. The obtained results are used to carry out an energy and economic analysis, which aims at assessing the feasibility and environmental benefits of the proposed system over conventional technologies.

Introduction

Sewage sludge management has become one of the most critical challenges in wastewater treatment plants (WWTPs). Indeed, although it represents a small percentage of wastewater treated in a plant, its handling accounts for up to 50% of the total operating costs [1]. In recent years, sludge production has increased for several reasons. The world population has increased and, at the same time, the population served by WWTPs has increased. Also, wastewater treatment has become more intensive due to the more stringent legislation, increasing the solids percentage that is removed from wastewater. The stringent legislation also concerns sludge disposal since the traditional options, such as direct utilization in agriculture and landfilling, need to be limited to make way for the recovery of useful materials and/or energy in a sustainable way [2].

Waste-to-energy has significantly expanded in recent decades including different feedstock, among which sewage sludge is recognized to be a valuable source of energy and materials [3,4]. In particular, energy recovery technologies are more effective in reducing sludge volume and pollutants and present a lower global warming potential compared to other treatment methods [5]. In WWTPs, energy recovery from sludge allows, on one hand, to reduce the waste to be disposed of, on the other hand, to reduce the energy purchase, which accounts for 25–50% of operating costs in WWTPs [6]. Therefore, from a wider perspective, it reduces greenhouse gas emissions related to road transportation and energy production, which are usually based on fossil fuels [7].

Energy from sludge can be recovered through either biological or thermochemical processes. Gasification is a promising thermochemical conversion process to produce useful energy forms from sewage sludge [8], and it presents several advantages over conventional combustion [9,10]. Indeed, gasification is carried out in an oxidant-restricted atmosphere, which limits the formation of dioxins, as well as sulfur and nitrogen oxides [11], and also reduces the amount of gas to be cleaned and consequently the cost of cleaning systems to be installed [12–14].

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Nomenclature

Roman Symbol

a
A
c
ΔCF
$\overline{C}_p$
G
H
h
ΔH_V
J
j
K_Y
L
LHV
$\dot{m}$
M
N
NPV
NPP
NTU
p
PER
$\dot{Q}$
q_L
R
SPB
T
$\dot{V}$
$\dot{W}$
X
Y

Acronyms

CGE
DB
ER
WWTP(s)

Greek Symbol

γ	- Ratio between specific heat at constant pressure and specific heat at constant volume
η	% Efficiency

Subscripts/Superscripts

0	
CHP	
Compr	
DF	
el	
Fuel	
G	
Gas	
I	Installation
in	
is	
LW	
ref	
Res	
S	
Sl	
Syng	
th	
Turb	
V	

Moreover, gasification associated to energy production appears to have a lower environmental impact compared to incineration [15,16]. In addition, phosphorus is released as a solid residue [17] making its recovery easier.

For these reasons, sludge gasification has been recently investigated by many authors, both experimentally and numerically, exploring different types of gasifiers and operating conditions.

Sludge gasification has been tested in small-scale downdraft gasifiers, obtaining syngas with a Lower Heating Value (LHV) around 4 MJ/m^3 and a Cold Gas Efficiency (CGE) around 60–65% [18,19]. Despite some authors have investigated downdraft reactors, fluidized beds are the most used to process sewage sludge due to the good gas–solid contact, mixing and flexibility [20,21]. Among them, in particular the bubbling fluidized bed reactors are reported to exhibit a larger technological strength and market competitiveness in regards to sewage sludge gasification with respect to the circulating fluidized beds [22]. Such reactors have been tested at a laboratory scale for gasification of sewage sludge, showing that, at a given equivalence ratio, larger throughput, which also means lower gas residence times, does not remarkably impact the CGE and the carbon conversion, but it increases the tar production [23]. It has been observed that the most influencing parameter is the equivalence ratio (ER) and the ER values in the range of 0.2–0.35 are suitable to optimize the gasification of sewage sludge [20,22]. Also, the temperature has been found to significantly affect the process, with higher efficiency observed at a higher temperature. However, this parameter has to be limited due to the risk of melting, agglomeration, and sintering of the sewage sludge ash.

Sewage sludge gasification in fluidized bed reactors has been investigated also at a larger scale. The successful operation of the process has been demonstrated in Balingen (with a throughput of 935 t/a ds) and Mannheim (with a throughput of 1955 t/a ds), in Germany, where the ER has been varied between 0.28 and 0.35 and the optimum temperature range has been observed to be between 800 and 870 °C [24].

Fewer works are available on sewage sludge gasification in bubbling fluidized bed reactors. Such works mostly focus on the effect of the bed properties on the process. Increasing the bed height can improve the process efficiency [25], using calcined dolomite [26] or alumina [27] as bed material may increase the production of H_2 as well as the tar removal in syngas.

As mentioned above, the advantage of gasification is the production of a useful energy vector [28] from sewage sludge. However, the use of syngas from sewage sludge for energy generation has not been widely investigated and the available papers focus mainly on the gasification process itself [29]. Due to the low organic content, the syngas obtained by sewage sludge gasification may cause problems when it is used for power production [30], such as unstable combustion in the engine [31,32] and power drop of about 1/3 if compared to a spark-ignition engine fueled with gasoline [33]. Using syngas from sewage sludge gasification in a spark-ignited internal combustion engine driving a power generator (16 kW/1500 rpm) has been investigated by Szwaja et al. [30]. To fix several malfunctions due to the relatively low calorific value of the syngas, methane enrichment has been investigated finding that a satisfactory engine run can be achieved with 40% vol of methane. A similar operation strategy has been proposed by Elsner et al. [29], where the authors suggested gasifying blends of sewage sludge and wood pellets (60%/40%) to increase the calorific value of the produced syngas and consequently the system performance.

Since few studies are available on the use of syngas from sewage sludge gasification in internal combustion engines, some data related to syngas from other biomasses are illustrated in Table 1.

Some authors proposed to use Combined Heat and Power (CHP) systems for energy generation from syngas. In the case of syngas from sewage sludge, the waste heat has been proposed to be used for sludge drying. Indeed, the moisture content of sewage sludge needs to be reduced for efficient gasification since it causes more active endothermic reactions, making keeping the temperature in the reactor difficult [34]. For this reason, sewage sludge is usually dried before gasification. Thermal drying is a highly energy-intensive process [35], therefore using waste heat from gasification may be crucial to reduce its energy consumption. As an example, the project SEDIS (Sewage Sludge Disposal with Energy Recovery through downscaled Fluidised Bed Gasification and CHP Units) has presented two processes to convert sewage sludge into useful energy on-site at the WWTP [36]. In both processes, waste heat from gasification is used for sludge drying, which is carried through a fluidized bed technology, and in one of the two systems, such waste heat is integrated with solar energy.

The use of syngas in an internal combustion engine has been proposed by Kokalj et al. [37], where two scenarios have been compared. Syngas has been supposed to be fed into the public natural gas grid or stored on-site in a reservoir to be used based on power demand periods. The first scenario is more convenient in terms of initial investment due to the use of the existing natural gas distribution network and energy recovering infrastructure, whereas the second scenario allows producing more power if complete onsite installation is available.

Different scenarios for energy production based on sewage sludge gasification have been also proposed by Alves et al. [49], where the techno-economic analysis for a small-scale gasification plant processing mixtures of solid recovered fuels and sewage sludge is presented. In that work, the two analyzed solutions are the production of electric energy and the production of hydrogen. Both the scenarios result economically feasible, with a lower payback period and higher internal rate of return in the first case, and a higher net present value in the second one.

In the present work, a cogeneration system based on sewage sludge gasification in a bubbling bed reactor is numerically analyzed. Syngas produced from gasification is used as a fuel in an internal combustion engine for combined heat and power production. Different solutions are compared: the internal combustion engine is supposed to be fuelled with syngas or with syngas and natural gas. The electrical energy produced by the system supplies a fraction of the energy demand of the WWTP, whereas the heat is used for thermal drying of the sludge produced into the plant. A WWTP of the Campania region, in southern Italy, where electricity is purchased from the grid, is considered as a case study.

The models developed to carry out the feasibility analysis of the proposed system, along with the main assumptions taken into account, are described in Section 2. Then, the results of the analysis are illustrated in Section 3 and the main conclusions are drawn in Section 4.

Methods

The integrated system developed in this work is illustrated in Fig. 1. The wet sewage sludge enters the dryer at ambient temperature and pressure (1) and is dried to a moisture content lower than 10% (2), using a hot drying stream (3). A fraction of the drying flow is recycled (4a) to increase the efficiency of the system and to reduce the flow rate of the exhausted to be treated (4b). The dry sludge (2) feeds a bubbling bed reactor gasifier that produces syngas (7) and char (6). The raw syngas is cleaned through a cyclone (7–8) that separates the coarse ash particles (9) and then cooled down through the heat exchanger (8–13), which is used to pre-heat fresh air used as a fraction of the drying flow (13–14). After cooling (10), syngas and eventually methane (11) power an internal combustion engine that produces electrical energy used to supply the dryer and a fraction of the WWTP demand and thermal energy employed to supply the dryer demand. When dual fuel operation is considered, the mass flow rate of methane needed to cover the entire thermal energy demand of the drying process is considered. When only syngas is used as a fuel, the exhausts (20) of a boiler powered by methane (18) are used to meet the thermal demand of the drying process.

As mentioned above, thermal energy for the drying process is supplied through a hot drying stream of which a fraction is recirculated. To replace the fraction of non-recycled drying flow, the exhaust gases of the engine (17) and fresh air (12) are supplied to the system. Fresh air is preheated (12–14) using the engine cooling water (12–13) and the hot syngas (13–14).

The proposed system is numerically simulated through the software Aspen Plus (Advanced System for Process Engineering) to assess its energy performance. The system can be divided into three sub-systems that are thermal drying, gasification, and energy production. Sewage sludge is modeled as a carbonaceous fuel [50], characterized by a particle size distribution, calculating the specific heat and density, and enthalpy through statistical correlations based on the biomass ultimate,

Table 1
Literature data on the operation of internal combustion engines fuelled with syngas from biomass gasification.

Ref.	Biomass	Syngas LHV (MJ/Nm^3)	Engine efficiency	Maximum capacity (kW)	Compression ratio	De-rating
[38]	Switchgrass	6.47 ± 0.7	21.3% (electrical)	9 (natural gas)	–	44%
[39]	Redwood pelletsWood chips	5.31–6.494.67–5.86	16.4% (electrical)19% (electrical)	56	10.25	–
[32]		5.179 (MJ/kg)	19.3%	5.5	–	–
[40]	Bagasse	–	31.6%	–	–	–
	Pine sawdust		30.7%			
	Poplar sawdust		30.9%			
	Almond shells		31.3%			
[41]	Agriculture residues	–	26–30% (electrical), 15–34% (thermal)	100–1000 kW_{th}	–	–
[42]	Beech chips	11.8 (MJ/kg)	41.9% (electrical), 43.8% (thermal)	3.1 MW_e (natural gas)	–	–
[43]	Wood chips	4–5 (MJ/kg)	23.3–24.5% (electrical) 61.3–61.7% (thermal)	–	–	–
[44]	Wood chips	–	21.8% (electrical), 46.1% (thermal)	–	–	–
[29]	Sewage sludge and wood pellets	5.2	28.9%* (electrical)	100 kW (liquified petroleum gas)	–	–
[45]	Rice husk	3.0–6.7 (MJ/kg)	26–28.5% (electrical), 19–21% (thermal)	1131 kW_e (natural gas)	12.5	32%*
[46]	–	3.813–5.294 (MJ/kg)	22–27% (electrical at partial load)	30 kW	–	–
[47]	Wood	–	28.5% (electrical), 43.9% (thermal)	–	–	34.6%*
[48]	Wood	3.77 ± (8.46 × 10^{-6})	28.1 ± 1.1% (electrical) 31.3 ± 7.6% (thermal)	20 kW_e	9.45	

*calculated from the data presented in the reference.

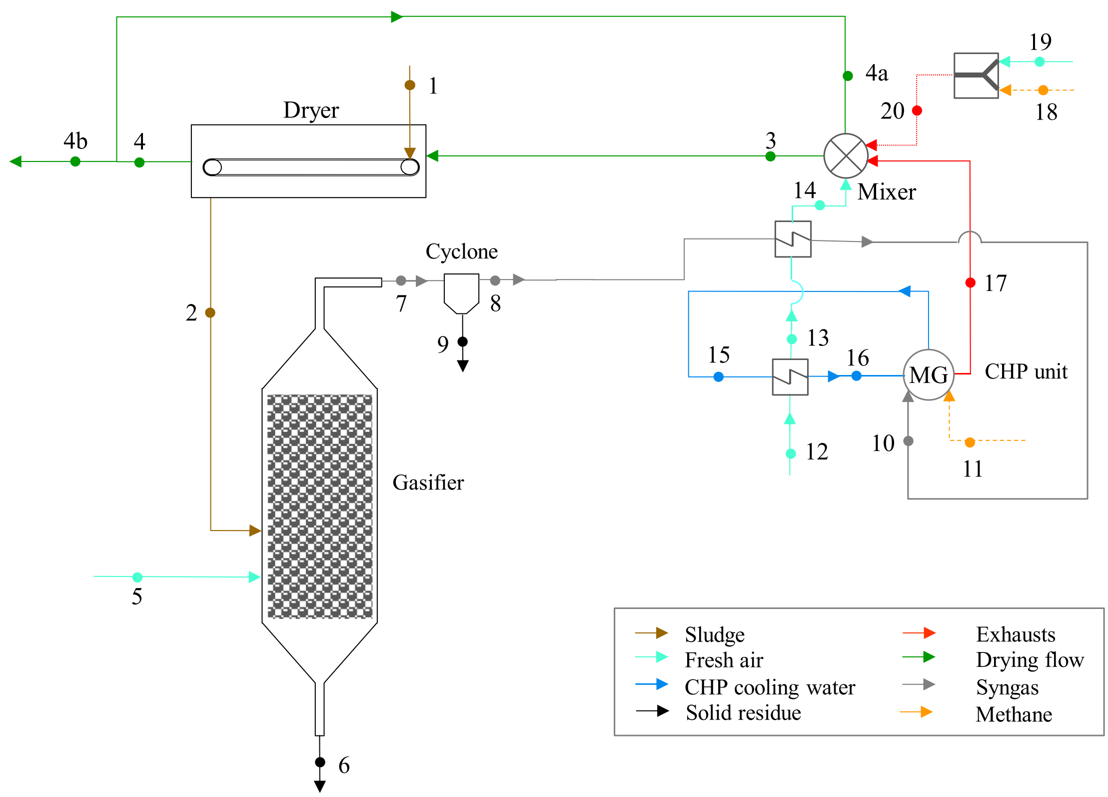


Fig. 1. Layout of the analyzed system.

proximate, and sulfur analyses [51]. In Aspen Plus such materials are modeled as "non-conventional" streams.

The Peng Robinson-Boston Mathias modified method is used to model the system since it deals with multiple phases, as well as conventional and nonconventional solids, and is suitable for high-temperature processes [52]. This method uses the Peng Robinson cubic equation of state with the Boston-Mathias alpha function for all the thermodynamic properties, which is suitable for the nonpolar or mildly polar mixtures such as hydrocarbons and light gases.

Thermal drying

ASPEN Plus provides built-in components to simulate thermal drying. In this work, a convective belt dryer is considered, due to its high flexibility and the possibility of adjusting its operation by managing the temperature and flow rate of the drying stream [53]. Thermal drying is analyzed considering the geometric parameters of the component and the thermodynamic parameters of the material flows.

The convective belt dryer, illustrated in Fig. 2, is modeled considering the following mass and heat balances [54]:

$$\dot{m}_{DF}Y_1 + \dot{m}_{Sl}X_1 = \dot{m}_{DF}Y_2 + \dot{m}_{Sl}X_2 \quad (1)$$

$$\dot{m}_{DF}h_1 + \dot{m}_{Sl}h_1 = \dot{m}_{DF}h_2 + \dot{m}_{Sl}h_2 + q_L \quad (2)$$

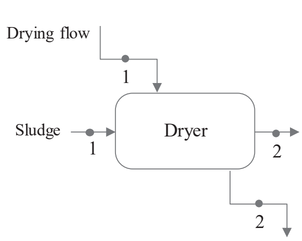


Fig. 2. Scheme of the thermal dryer.

Where $\dot{m}_{DF}$ is the mass flow rate and Y is the humidity, both on a dry basis, of the Drying Flow (DF), $\dot{m}_{Sl}$ is the mass flow rate and X is the moisture content of sludge (Sl), h is the specific enthalpy and q_L represents the rate of heat loss from the system. The numbering refers to the sketch of Fig. 2.

The Drying Flow is a vapor–gas mixture, whose specific enthalpy, h_{DF}, can be assumed as the sum of the specific enthalpies of the Gas and the Vapor, as:

$$h_{DF} = \overline{C}_{p,G}T + \left[\overline{C}_{p,LW}T_S + \Delta H_V + \overline{C}_{p,V}(T - T_S)\right]Y \quad (3)$$

where $\overline{C}_{p,G}$, $\overline{C}_{p,LW}$ and $\overline{C}_{p,V}$ are the average specific heats of dry Gas, Liquid Water and Vapor, respectively, T is the temperature, ΔH_V is the latent heat term for water vaporization, and the subscript S represents the saturation condition. As mentioned above, for carbonaceous materials, as sewage sludge, enthalpy is derived through correlations based on ultimate and proximate analyses.

The kinetics of the process is considered implementing an experimental drying curve [55], that delineates the rate of moisture loss as the material dries out. To determine the temperature and drying-rate profile, an index of performance of the dryer, called Number of Transfer Units, NTU, is defined as [54]:

$$NTU = ln\frac{Y_S - Y_{G,in}}{Y_S - Y_G} = \frac{K_Y A L}{G} \quad (4)$$

Where K_Y is the mass transfer coefficient for humidity differences, A is the interfacial area per unit dryer volume, L is the length of the dryer, G is the specific dry Drying Flow and the subscript *in* represents the initial condition.

Gasification

Aspen Plus does not provide a built-in component to simulate gasification. A component that models the minimization of the Gibbs free energy of the system is commonly used in the literature to investigate biomass gasification [56–59]. Therefore, such a component, together with other blocks provided by Aspen Plus and some external subroutines written in FORTRAN, is used to simulate the gasification process.

A scheme of the model developed in Aspen Plus is reported in Fig. 3.

The dried sludge is fed into a decomposition reactor, used to decompose non-conventional streams, such as sludge, into its constituent elements (carbon, hydrogen, nitrogen and oxygen), water and ash. Indeed, the reactor that simulates chemical equilibrium by minimizing Gibbs free energy cannot deal with non-conventional components. The RYield Reactor is used as a decomposition block since stoichiometry and kinetics are unknown, but a yield distribution is available. The mass yields of the RYield reactor are determined and set starting from the data of ultimate and proximate analyses by using a subroutine written in FORTRAN.

A heat stream connects the decomposition and the gasification reactors to account for the difference in enthalpy between the original stream and the decomposed one.

The outlet stream from the decomposition block enters a separator to remove unreacted char before the gasification reactor. As mentioned above, for the gasification reactor an RGibbs is used, where the sludge and the hot gasifying agent are fed and additional heat is supplied to sustain the process.

The unconverted char is heated up to the gasifier temperature and then mixed with the gas stream leaving the gasifier. Finally, the unreacted char and ash are separated from the raw syngas through a cyclone.

It is well known that the gasification process does not straightforwardly reach the chemical equilibrium state due to the short residence time of gases in the reactor. Therefore, to better simulate the non-equilibrium conditions of real gasifiers, a modified equilibrium model for sludge gasification is set by implementing a restricted chemical equilibrium, as proposed in [60]. The restricted equilibrium is performed by specifying a temperature approach, which represents the difference between the chemical equilibrium temperature and the real reactor temperature. Essentially, the reaction equilibrium is moved towards the reagents or products so as to better simulate the nonequilibrium conditions of the real gasifier.

The reactions (5) to (10) are considered to occur during sewage sludge gasification.

$$C + H_2O \leftrightarrow H_2 + CO \text{ Water Gas} \tag{5}$$

$$C + O_2 \leftrightarrow CO_2 \text{ Carbon combustion} \tag{6}$$

$$C + 2\, H_2 \leftrightarrow CH_4 \text{ Methanation} \tag{7}$$

$$CO + H_2O \leftrightarrow H_2 + CO_2 \text{ Water Gas Shift} \tag{8}$$

$$C_2H_4 + 3\, O_2 \leftrightarrow 2\, H_2O + 2\, CO_2 \text{ Ethylene combustion} \tag{9}$$

$$H_2 + 0.5\, O_2 \leftrightarrow H_2O \text{ Hydrogen combustion} \tag{10}$$

The following assumptions are considered for the simulation of the sludge gasification:

- the process is considered to be steady-state, no transient state is modeled;
- gasification is assumed to be run isothermally;
- the model is zero-dimensional and kinetic-free;
- sludge devolatilization occurs instantaneously at the entrance of the reactor;
- syngas is modeled as a mixture of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), moisture (H_2O), ethylene (C_2H_4) and ethane (C_2H_6);
- pressure for all components is set to atmospheric pressure;
- the formation of the tars and other heavy products is neglected.

Handling tar formation is still one of the biggest challenges in modeling gasification processes and there is still no consensus in the literature [61]. Extensive discussions on modeling the formation of tar in the gasification process are not within the focus of this paper and can be found elsewhere [62–64]. More details on the model adopted herein, as well as its validation, can be found in [65].

The performance of gasification can be assessed through the CGE, an index that represents the ratio between the energetic value of the produced syngas and the energy in the biomass fed in the gasifier:

$$\eta_{CGE} = \frac{\dot{m}_{Syng} \bullet LHV_{Syng}}{\dot{m}_{Sl} \bullet LHV_{Sl}} \tag{11}$$

where $\dot{m}_{Syng}$ and LHV_{Syng} are the mass flow rate and the lower heating value of the produced syngas and LHV_{Sl} is the lower heating value of the treated biomass.

To assess the efficiency of the gasification from an energy point of view, the net primary power available from the process is estimated as:

$$NPP = \dot{m}_{Syng} \bullet LHV_{Syng} - \frac{\dot{Q}_{Gas}}{\eta_{th}} \tag{12}$$

where $\dot{Q}_{Gas}$ is the thermal power supplied to carry out gasification and η_{th} is a reference thermal efficiency.

Cogeneration unit

As commonly supposed in the available literature, to represent the behavior of a combustion engine where the reaction with air occurs, compressors, chemical reactors, turbines, and heat exchangers are used to model isentropic compression, combustion at constant volume, isentropic expansion and cooling at constant volume [66,67].

Both compressor and turbine work at fixed isentropic efficiency. The isentropic efficiency refers to the deviation from the reversible, adiabatic work, and is calculated for the compressor, $\eta_{is,Compr}$, and the turbine, $\eta_{is,Turb}$, as:

$$\eta_{is,Compr} = \frac{(p_2/p_1)^{(\gamma-1)/\gamma} - 1}{T_2/T_1 - 1} \tag{13}$$

$$\eta_{is,Turb} = \frac{T_2/T_1 - 1}{(p_2/p_1)^{(\gamma-1)/\gamma} - 1} \tag{14}$$

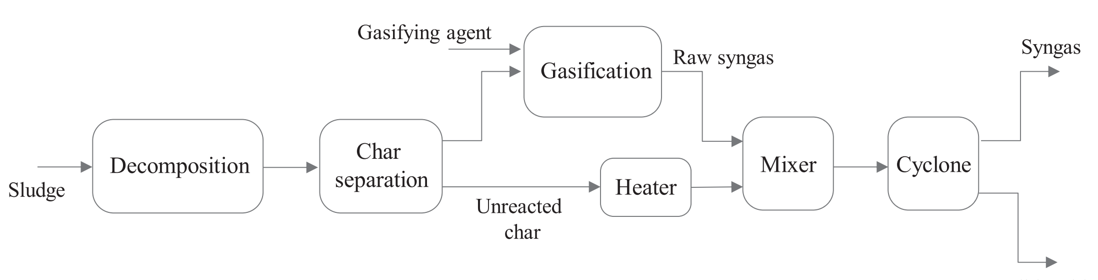


Fig. 3. Scheme of the model developed in Aspen Plus to simulate gasification process.

where the subscripts *1* and *2* refer to the inlet and outlet conditions, respectively, and γ to the ratio between specific heat at constant pressure and specific heat at constant volume.

The isentropic expansion and compression coefficients are defined by calibrating the model through experimental data available in the literature. For the sake of completeness, some examples proposed in the literature are presented in Table 2.

The combustion chamber is modeled as an RGibbs operating at the compressor outlet pressure. The air mass flow rate entering the combustion chamber is calculated to guaranty the best engine performance, considering an excess in relation to the amount of stoichiometric oxygen needed for the combustion reactions. It is assumed that H_2, CO, CH_4, C_2H_4 and C_2H_6 participate as fuels in combustion reactions. To simulate heat losses, the reactor is assumed to be nonadiabatic by setting an exiting thermal stream.

The low-grade heat is estimated through a heat exchanger that cools the turbine exhausts up to the common temperature at which they are released in conventional internal combustion engines.

Economic and environmental assessment

The feasibility of the proposed system is assessed through an economic analysis. The economic model is based on several indexes, dependent on the investment and the operating costs.

The investment cost of the gasifier can be derived as a function of its thermal power [69]. The specific investment cost for the CHP units, j_{CHP}, can be determined as [70]:

$$j_{CHP} = 4639 \bullet W_{el}^{-0.333} \tag{15}$$

The maintenance costs, *M*, of the whole system are supposed to be 5.00% of the total investment cost, J_0[71]:

$$J_0 = J_{Gas} + J_{CHP} \tag{16}$$

J_0 is increased by 20.0% to account for the installation costs,J_I. The energy production of CHP unit allows reducing economic expenses related to the purchase of electricity from the grid to supply the plant facilities and of fuel to produce heat for thermal drying. The revenue due to electric energy saving, $R_{el,CHP}$, is defined as:

$$R_{el,CHP} = c_{el} \bullet \dot{W}_{el,CHP} \bullet H \tag{17}$$

where c_{el} is the specific cost for electric energy purchase, $\dot{W}$ is the saved electrical power, and *H* represents the yearly hours of operation. The thermal demand of sludge drying is partially or completely, depending on the configuration, supplied by the CHP unit. To determine the related revenue, the volumetric flow rate of methane, $\dot{V}_{Fuel,ref}$, needed by a boiler to provide the same thermal energy is calculated. The related revenue is equal to:

$$R_{Fuel} = \dot{V}_{Fuel,ref} \bullet c_{Fuel} \bullet H \tag{18}$$

where c_{Fuel} is the specific cost of methane. Due to gasification, the proposed system allows avoiding also the cost for sludge disposal, which is calculated as:

$$R_{Sl} = \dot{m}_{Sl} \bullet c_{Sl} \bullet H \tag{19}$$

where $\dot{m}_{Sl}$ is the mass flow rate of gasified sludge and c_{Sl} is the specific cost for its disposal.

The economic indexes used for the analysis are the Simple PayBack, *SPB*, and the Net Present Value, *NPV*, which are reported in Equations (20) and (21), respectively.

$$SPB = \frac{J_0 + J_I}{\Delta CF} \tag{20}$$

$$NPV = -(J_0 + J_I) + \sum_{i=1}^{N} \frac{\Delta CF}{(1+a)^i} \tag{21}$$

where *a* is the discounting rate, equal to 7.00%, and *N* is the service life, equal to 15 years. An overhaul of the system, whose cost is supposed to be 30.0% of the total investment cost, is considered during the 7th year. ΔCF is the annual economic saving, which is the sum of the revenues and the operational costs of the system:

$$\Delta CF = R_{el,CHP} + R_{Fuel} + R_{Sl} - C_{fuel} - M - C_{Res} \tag{22}$$

where the cost for the fuel, C_{fuel}, and that for the solid residue of the process, C_{res}, are calculated as:

$$C_{Fuel} = \dot{V}_{Fuel} \bullet c_{Fuel} \bullet H \tag{23}$$

$$C_{Res} = \dot{m}_{Res} \bullet c_{Res} \bullet H \tag{24}$$

in which $\dot{V}_{Fuel}$ is the volumetric flow rate of methane used by the proposed system, $\dot{m}_{Res}$ is the mass flow rate of the solid residue of the gasification process and c_{Res} is the specific cost for its disposal.

Power generation technologies based on the use of biomass are usually more sustainable in terms of environmental impact compared to reference solutions [72]. To assess the environmental performance of the system the Primary Energy Ratio (*PER*) is calculated as:

$$PER = \frac{Usefulenergy}{Primaryenergy(nonrenewable)} \tag{25}$$

Results and discussion

Input parameters

A feasibility analysis of the proposed system is carried out for a WWTP located in the Campania region, Southern Italy, which serves an equivalent population of 1,200,000 inhabitants, with an electrical energy demand of 31,916 MWh/year and a sludge production of 36,498 t/year. Sludge ultimate and elemental analyses are reported in Table 3.

The main input parameters assumed for the simulation are summarized in Table 4.

For the gasification, ER and temperature are varied to identify the best conditions in terms of energy recovery. The ranges are defined considering the conditions suggested in the literature [20,22,65]. For the sake of completeness, the ER is defined as the fraction between the actual air–fuel ratio and the stoichiometric air–fuel ratio.

For the drying process, the sludge mass flow rate and its moisture content are provided by the WWTP manager.

The input parameters of the CHP unity, when syngas or syngas and natural gas are considered as fuel, are derived by calibrating the model through the experimental data reported in [30]. More in detail, a sensitivity analysis is carried out by varying isentropic efficiency for

Table 2
Literature data on the simulation of internal combustion engines fuelled with syngas from biomass gasification in Aspen Plus.

Ref.	Isentropic expansion coefficient	Isentropic compression coefficient
[48]	87%	85%
[68]	90%	90%
[67]	–	70%
[66]	90%	–

Table 3
Main properties of the sludge, .

Proximate analysis	Unit	Value	Ultimate analysis	Unit	Value
Volatile matter	$\%_{wt,db}$	59.67	C	$\%_{wt,db}$	31.89
Fixed carbon	$\%_{wt,db}$	5.63	H	$\%_{wt,db}$	5.51
Ash	$\%_{wt,db}$	34.7	N	$\%_{wt,db}$	3.84
			O	$\%_{wt,db}$	24.06

adapted from [73]

Table 4
Input thermodynamic parameters of sludge and fresh air.

Process	Parameter	Unit	Value
Gasification	Equivalence ratio (ER)	–	0.100 ÷ 0.400
	Fresh air inlet temperature, T_{11}	°C	25.0
	Fraction of unconverted char	–	0.22
	Gasification temperature	°C	720 ÷ 840
Cogenerationunit	Compression ratio	–	10.5:1
	Air–fuel equivalence ratio	–	1.10
	Turbine exhausts temperature	°C	390
Drying	Mass flow rate of sludge (wet basis),$\dot{m}_{Sl,1}$	t/y	36,500
	Sludge inlet temperature, T_1	°C	25.0
	Sludge inlet moisture content, X_1	%	70.0
	Fresh air inlet pressure, p_{17}	bar	1.00
	Fresh air inlet temperature, T_{17}	°C	25.0
	Recycled fraction of desiccant flow	%	55.0
Economics	Electricity purchase	€/MWh	180
	Methane cost	€/Nm^3	0.329
	Disposal cost of solid residue	€/t	50.0
	Methane LHV	MJ/Nm^3	35.7
	Operation hours	h/y	7000

both compressor and turbine between 0.7 and 0.9, as suggested in the available literature (Table 2) and heat losses between 5 and 15%, in order to match the experimental values. A similar procedure is used to calibrate the model for the simulation of an internal combustion engine fueled with methane [74] that is used as a reference case for the economic and environmental analyses.

For the economic analysis, the cost of electricity is provided by the WWTP, while for methane the average price for non-households consumers in EU-28 countries of natural gas, considering the data between 2008 and 2018, is adopted [20].

Gasification

The main results related to the gasification process are reported from Fig. 4 to Fig. 7. Since the aim of the work is to propose an energy-efficient solution for wastewater treatment plants, the analysis of the gasification process is intended to identify the operating conditions that maximize energy recovery from syngas. For this reason, a sensitivity analysis is carried out by varying the process temperature and the ER.

Fig. 4 shows the syngas composition as the temperature (i) and the ER (ii) vary, respectively.

In agreement with the literature [75,76], the mole fraction of CO and H_2 increases with gasification temperature. The increase in the concentration of CO and H_2 may be related to the intensification of the water gas and water gas shift reactions at higher temperatures. CO_2 presents an inverse trend with temperature compared to CO, since their formation mainly depends on the C conversion, with water gas reaction appearing to be predominant compared to carbon combustion at higher temperatures. However, at the same time, as the temperature increases, the oxidation of CO to CO_2 rises, reducing the decrease of CO_2 molar fraction.

CH_4 concentration is almost constant with temperature, with an initial slight increase that can be connected to tar cracking and a final decrease that could be attributed to the cracking of CH_4.

Regarding the effect of the ER, the concentration of CO and CO_2 is almost constant. These compounds appear to be little influenced by the dilution on one hand because of their higher concentration, on the other hand, because their formation is driven by O_2 whose presence in the gasifier rises with the ER. As expected, the concentration of H_2, CH_4 and C_2H_4 decreases as the ER increases, since the combustion reactions are predominant due to the increasing presence of O_2.

Fig. 5 illustrates the variation of LHV and mass flow rate of syngas with the gasification temperature (i) and ER (ii), respectively. As found in the available literature [8,20,50,75,77], LHV and mass flow rate of syngas are significantly influenced by the ER, whereas the process temperature has a slight effect on these parameters. However, as the temperature increases, a slight increase of both the LHV and the mass flow rate of syngas can be observed; this can be due to the endothermal gasification reactions that perform better at higher temperatures [20]. The decrease of the LHV and the increase of the mass flow rate of syngas with the ER can be easily related to the dilution of syngas in nitrogen due to the increase of the mass flow rate of gasifying agent.

Obviously, the trends of LHV and mass flow rate and syngas significantly influence the net primary power available from sludge gasification that depends on the primary power of syngas and the thermal power required to carry out the gasification process, shown in Fig. 6.

The primary power of syngas is significantly influenced by its LHV then it increases with the process temperature and decreases with the ER. The thermal power required to carry out the process has the same trend. Increasing the gasification temperature allows increasing the process performance, in terms of LHV and mass flow rate of syngas, but it rises the external demand for thermal power. Increasing the ER allows compensating this effect, since the influence of exothermic combustion reactions becomes more significant, lowering the external demand of thermal power so much that at high ERs the process is almost energy self-sufficient. Therefore, assuming that the external demand for thermal power for gasification is satisfied by using the same syngas in a boiler, the net primary power can be determined. There is a slight

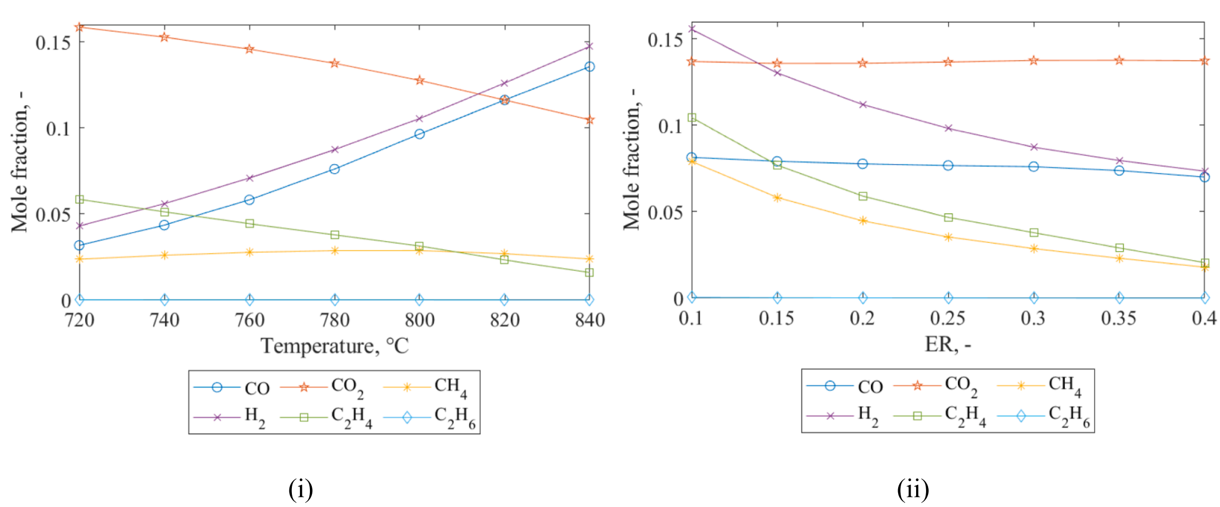
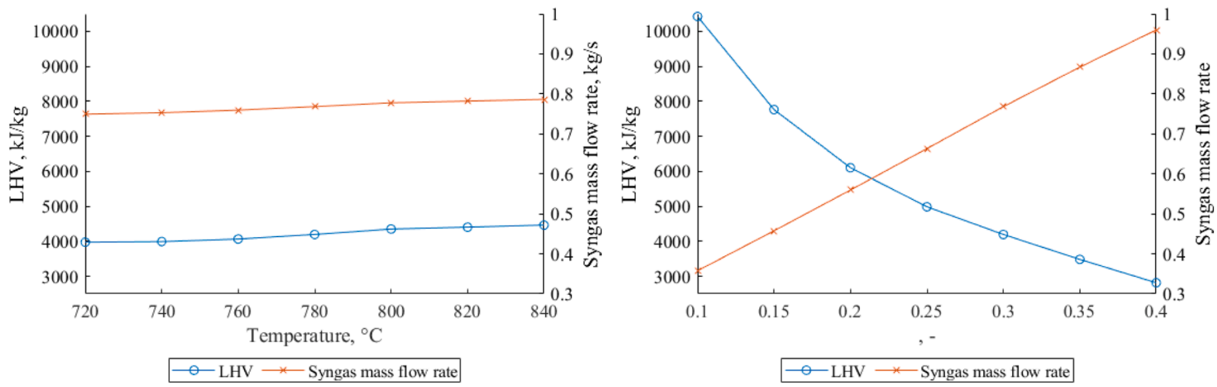
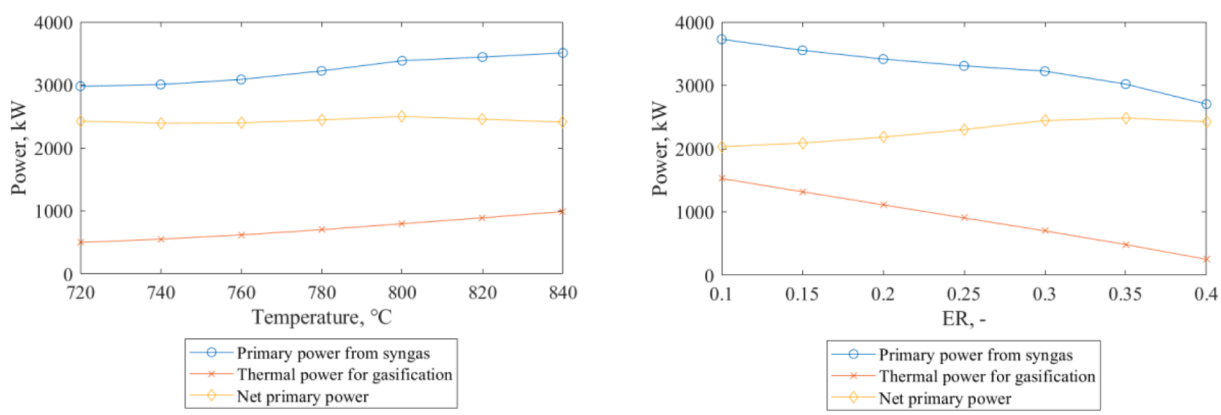


Fig. 4. Dry syngas composition (N_2 is not plotted to improve the readability of the picture): variation with gasification temperature (i) and ER (ii).



(i) (ii)

Fig. 5. LHV and mass flow rate of syngas: variation with gasification temperature (a) and ER (b).



(i) (ii)

Fig. 6. Primary power from syngas, thermal power needed for gasification and net primary power: variation with gasification temperature (i) and ER (ii).

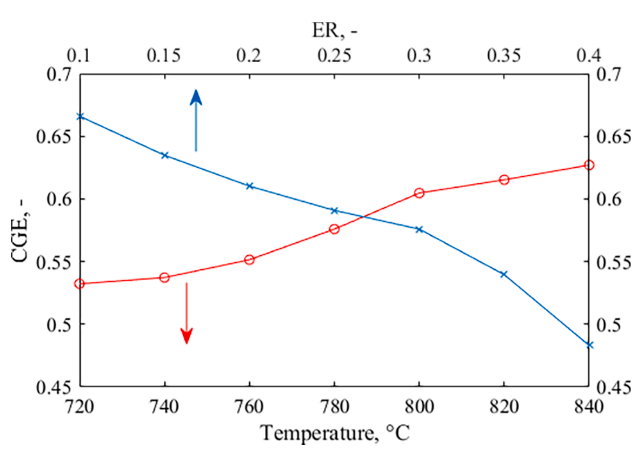


Fig. 7. CGE.

variation of this parameter with temperature, with an increasing trend up to 800 °C for the reasons discussed above. However, beyond this value, the increase in the process performance allows compensating the need for external thermal demand.

Concerning the effect of the ER, it appears that the effect of decreasing external thermal power demand prevails on the decrease of the process performance, causing a general increase of the net primary power available from syngas with the ER.

It is important to consider the trend of the net primary power since the conventional performance indexes used for gasification, such as syngas LHV or CGE, do not account for the external energy requirements of the process.

The effect of varying the gasification temperature and the ER on the CGE is shown in Fig. 7. As mentioned above, both the LHV and the mass flow rate of syngas increase with the gasification temperature and consequently the CGE. The trend is opposite when the ER increases due to the higher impact of LHV decrease compared to the syngas mass flow rate increase. This is coherent with the decrease of primary power available from syngas. However, as mentioned above, when the thermal power demand for carrying out the process is also taken into account, increasing the ER has a positive effect in terms of net primary power available from syngas.

Cogeneration unit

For combined heat and power production different solutions are numerically investigated, taking into account the experimental results of the use of syngas from biomass gasification available in the literature. To calibrate the model developed to simulate an internal combustion engine fueled with syngas or syngas and methane, the experimental data reported in [30] are considered. A sensitivity analysis on the isentropic coefficients for expansion and compression as well as on the combustion efficiency is carried out to identify the values that match the experimental results. The same procedure is used to calibrate the model for the simulation of an internal combustion engine fueled with methane [74] that is used as a reference case for the economic and environmental analyses. In this case, the range of the isentropic efficiencies considered for the sensitivity analysis is larger compared to the one identifies for syngas or syngas and methane due to the higher efficiency of methane-fueled engines. The values identified through the sensitivity analysis and the comparison between the brake thermal efficiency obtained through the numerical model and the experimental data are shown in Table 5 and Fig. 8, respectively. For the sake of completeness, the percentage in volume of syngas and methane in dual-fuel system is 40%-60%.

The electrical and thermal efficiencies of the engine as well as the electrical and thermal power at different conditions of gasification temperature and ER, for the cases of syngas engine and duel fuel (syngas and methane) engine, are shown in Fig. 9 and Fig. 10, respectively. For the sake of completeness, the ranges of variation and the value of gasification temperature and ER in correspondence of which the maximum efficiency is reached are shown in Table 6.

The efficiencies slightly vary in the analyzed ranges of gasification temperature and ER for both the cases taken into account. Such a variation is slightly more pronounced for the electrical efficiency rather than the thermal one with a higher impact of the ER compared to the gasification temperature. Focusing on the ER, due to its more significant effect, the highest efficiencies, both electrical and thermal, are reached at the lowest value taken into account for both the analyzed cases, due to the highest LHV of syngas. The lowest ER allows maximizing also the electrical and thermal power with the dual-fuel engine, whereas when only syngas is used as a fuel the highest ER appears to be more convenient, probably due to the higher net primary energy available from syngas. Finally, as expected, it is worth noticing that dual-fuel operation allows increasing the engine efficiency, especially the electrical one, due to the higher LHV of methane. In terms of electrical energy production, the analyzed system allows supplying between 9.3 and 10.8% and between 28.8 and 30.7% of the WWTP demand when the syngas engine or the dual-fuel engine is used, respectively.

For the sake of completeness, the efficiency and the power obtained with the methane engine are shown in Table 7.

In this case, the electrical energy produced allows supplying 52.4% of the WWTP demand. The values related to the engine fueled with methane are used to carry out the comparative economic and environmental analysis illustrated in Section 3.5.

Thermal drying

The process aims at reducing the moisture content up to 10% to make the sludge suitable for gasification. When the syngas engine is considered, a methane boiler is employed to supply the thermal demand that is not covered by the engine. Conversely, the dual-fuel system is sized to supply the entire thermal demand of the drying process. The comparison between the mass flow rate of methane used in the syngas engine and that employed in the dual fuel one is shown in Fig. 11. In both the cases and for both the sensitivity analyses, the mass flow rate of methane is almost doubled when the dual-fuel engine is employed. However, it has to be taken into account that also electrical energy is produced, increasing both the economic and environmental benefits of the system. As mentioned above, a methane engine is used for comparison.

Table 5
Input parameters for the numerical model of the cogeneration unit.

Parameter	Syngas, Syngas and methane	Methane
Isentropic expansion coefficient	0.90	0.98
Isentropic compression coefficient	0.80	0.91
Combustion efficiency	0.85	0.95

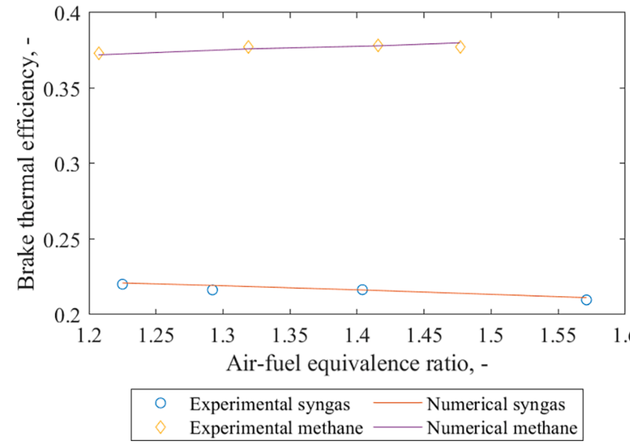


Fig. 8. Comparison between experimental and numerical values of brake thermal efficiency.

Sizing it to serve the thermal energy of the drying process, its fuel consumption is 0.144 kg/s. This means that syngas in dual-fuel operation allows saving around 45% of methane.

The drying process is carried out at around 160 °C. The thermal energy for the process is supplied by the syngas cooling, the CHP unit and, as mentioned above, the methane boiler when only syngas is considered to fuel the engine. As shown in Fig. 12 and Fig. 13, the highest fraction of thermal energy is recovered from the CHP: between 51 and 60% when only syngas is used as a fuel, and between 78 and 89% when the dual-fuel configuration is considered. In both cases, the ER variation has the highest impact.

Economic and environmental assessment

The system appears to be economically feasible with a SPB that does not exceed 1.4 years in the worst case of those taken into account. As shown in Fig. 14, both the SPB and the NPV present a slight variation with gasification temperature especially for the case of the syngas engine, for which the difference between the best and the worst case is 0.8%. The highest economic convenience is reached at a gasification temperature equal to 800 °C, in both the analyzed cases. The ER has a higher impact, especially for the case of syngas engine, for which the difference between the best and the worst case is around 5%. The highest economic convenience is reached at an ER equal to 0.35 when only syngas is used as a fuel and at 0.30 when the dual-fuel configuration is considered.

For the sake of comparison, the economic results related to the engine fueled with methane are calculated. As expected, the SPB, equal to 0.473 y, is lower compared to that obtained for the proposed solutions, even with the operating conditions that maximize the economic performance. However, in terms of NPV, the proposed solutions are comparable to the conventional one.

To investigate the economic feasibility of the proposed system, the investment costs and the annual economic revenues and costs obtained in correspondence of the operating conditions that maximize the economic performance are illustrated in Fig. 15 and Fig. 16, where also the results related to the conventional configuration are plotted. For the sake of clearness, the cases illustrated in these figures are: syngas engine (T = 800 °C, ER = 0.3) (a), dual fuel engine (T = 800 °C, ER = 0.3) (b), syngas engine (T = 780 °C, ER = 0.35) (c), dual fuel engine (T = 780 °C, ER = 0.30) (d), engine fueled with methane (e). The highest investment cost of the proposed solution is related to the gasifier, which accounts for 86% of total investment costs when only syngas is used as a fuel (cases a and c) and for 75% for the dual-fuel configurations (cases b and d). Obviously, due to the high impact of the gasifier, the conventional system (case e) is significantly more convenient in terms of investment

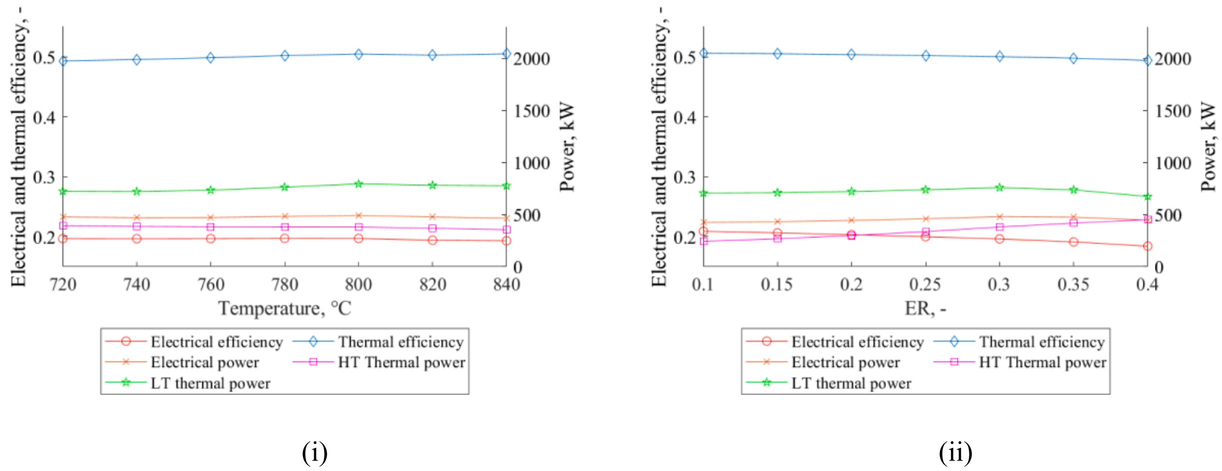


Fig. 9. Electrical and thermal efficiency and electrical and high temperature (HT) and low temperature (LT) thermal power for the syngas engine: variation with gasification temperature (i) and ER (ii).

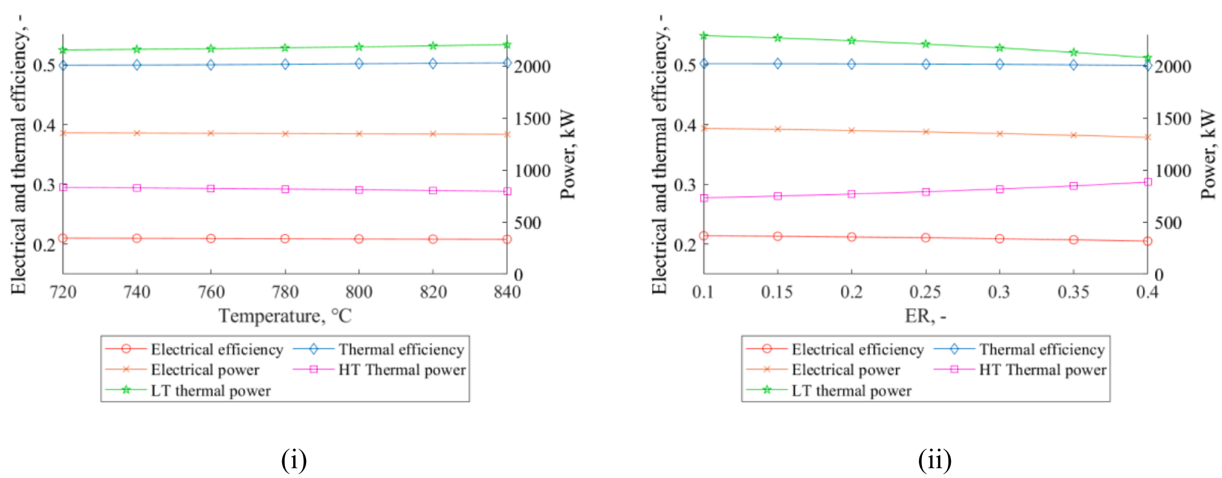


Fig. 10. Electrical and thermal efficiency and electrical and high temperature (HT) and low temperature (LT) thermal power for the dual-fuel engine: variation with gasification temperature (i) and ER (ii).

Table 6
Ranges of variation of electrical and thermal efficiency, electrical and thermal power for both the analyzed cases.

Case		Electrical efficiency		Thermal efficiency		Electrical power, kW		Thermal power, kW	
		Range	Max	Range	Max	Range	Max	Range	Max
Syngas engine	T sensitivity	0.193–0.197	780 °C	0.493–0.505	840 °C	470–492	800 °C	1116–1173	800 °C
	ER sensitivity	0.184–0.209	0.1	0.494–0.506	0.1	424–446	0.4	949–1123	0.4
Dual fuel engine	T sensitivity	0.208–0.210	720 °C	0.499–0.503	840 °C	1344–1358	720 °C	2987–3000	840 °C
	ER sensitivity	0.205–0.214	0.1	0.499–0.502	0.1	1315–1400	0.1	2964–3026	0.1

Table 7
Results related to the internal combustion engine fueled with methane.

Parameter	Unit	Value
Electrical efficiency	–	0.332
Thermal efficiency	–	0.416
Electrical power	kW	2389
High-temperature thermal power	kW	784
Low-temperature thermal power	kW	2213

costs.

The cost for the CHP system doubles in the dual-fuel configurations (cases b and d) compared to the solutions where syngas is used as a fuel (cases a and c). However, at the same time, the revenue from electrical energy production almost triples. This, despite the increase in fuel consumption, allows increasing the economic convenience as indicated by the lower SPB and the higher NPV. The significant effect of the revenue due to the electrical energy production is noticeable also for the case of the conventional system (case e). However, this effect does not allow balancing the absence of the revenue due to the avoided sludge disposal that is obtained through gasification. Indeed disposal of sewage sludge has become a critical issue for WWTPs due to its relevant financial and energy cost [78]. Moreover, the disposal cost has increased due to the increase of sludge production and the concern for its landfilling, since European legislation is promoting waste reuse and recovery. As an example, recently in Italy it exceeded 150 €/t [79]. For this reason, the effect of sludge disposal cost on the economic convenience of the proposed system is assessed, by taking into account also the

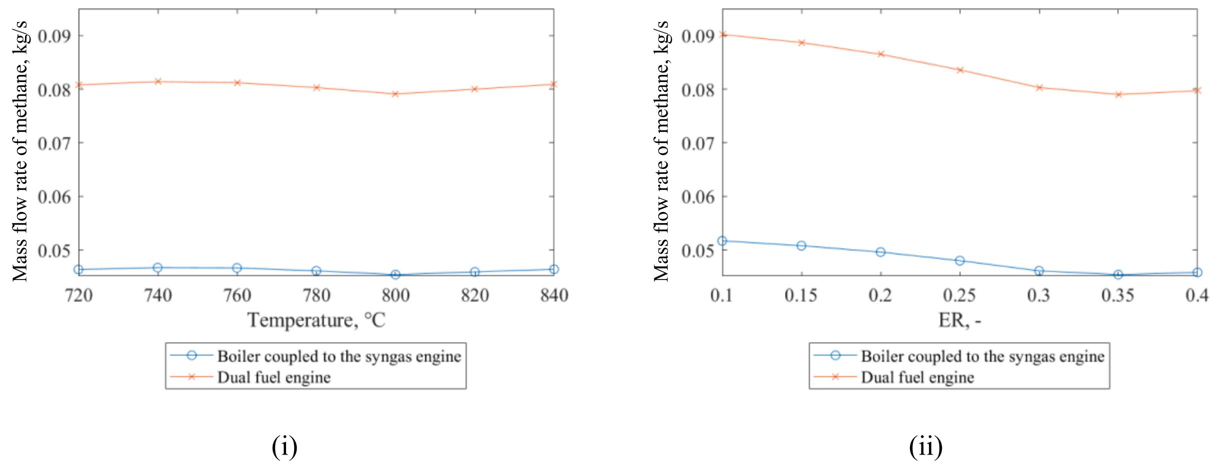


Fig. 11. Mass flow rate of methane used in the boiler coupled to the syngas engine and in the dual-fuel engine: variation with gasification temperature (i) and ER (ii).

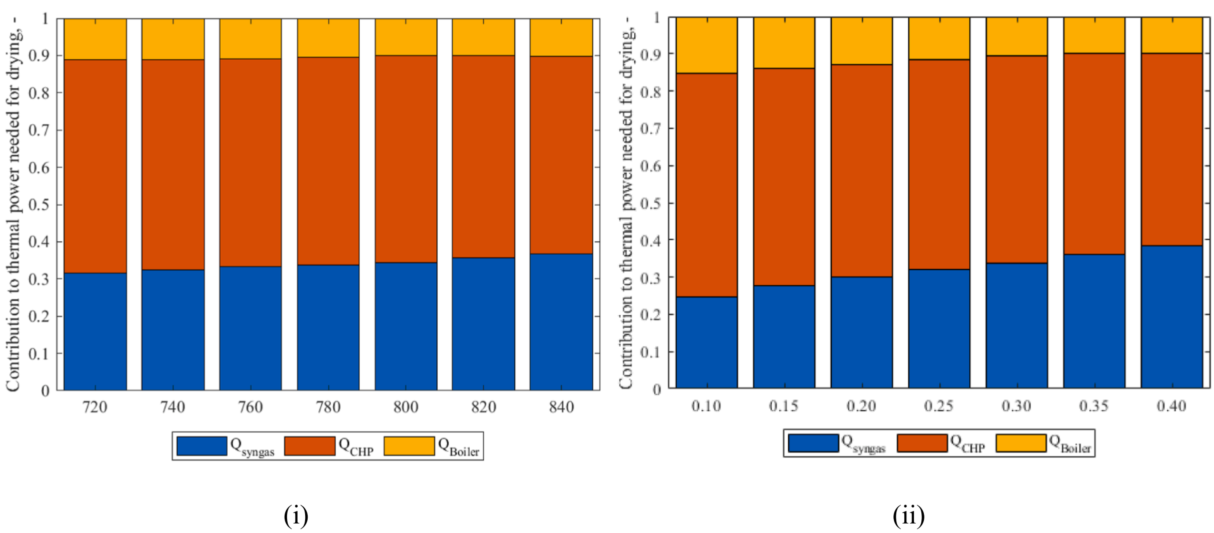


Fig. 12. Thermal power for sludge drying in the configuration of the boiler coupled to the syngas engine: contribution of syngas cooling (Q_{syngas}), CHP (Q_{CHP}), and boiler (Q_{Boiler}), variation with gasification temperature (i) and ER (ii).

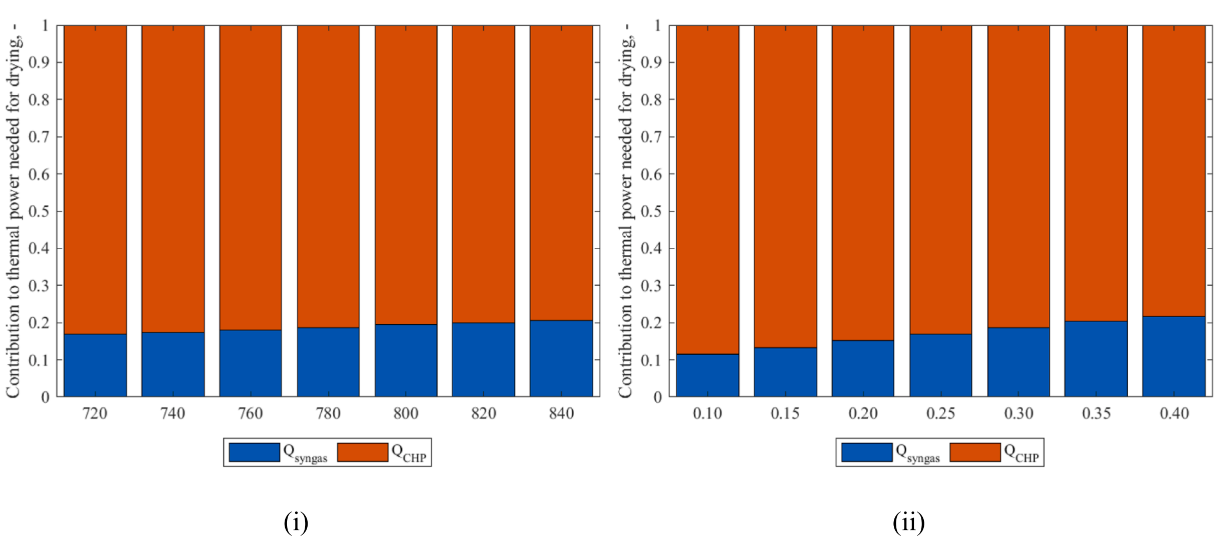


Fig. 13. Thermal power for sludge drying in the dual-fuel engine configuration: contribution of syngas cooling (Q_{syngas}) and CHP (Q_{CHP}), variation with gasification temperature (i) and ER (ii).

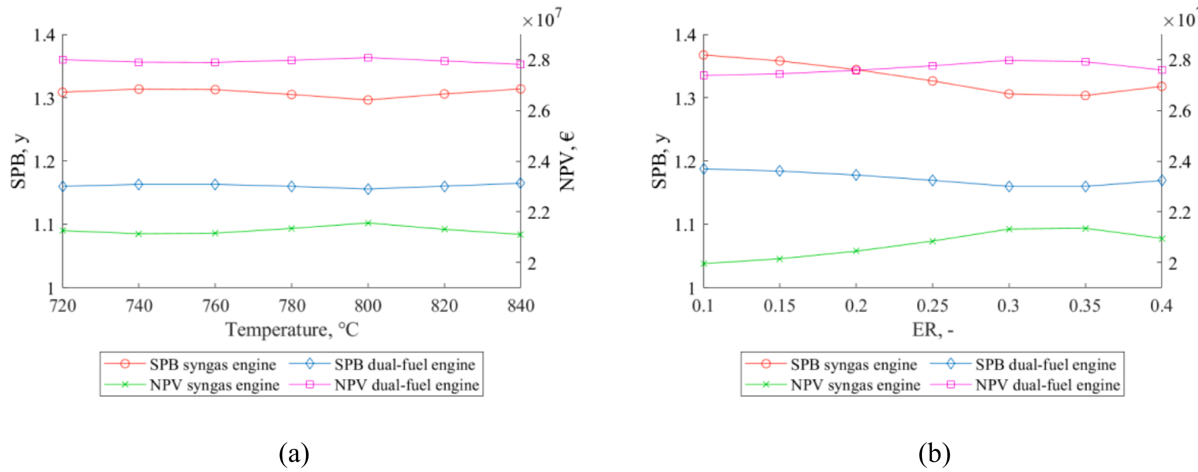


Fig. 14. Simple Pay Back and Net Present Value: variation with gasification temperature (a) and ER (b).

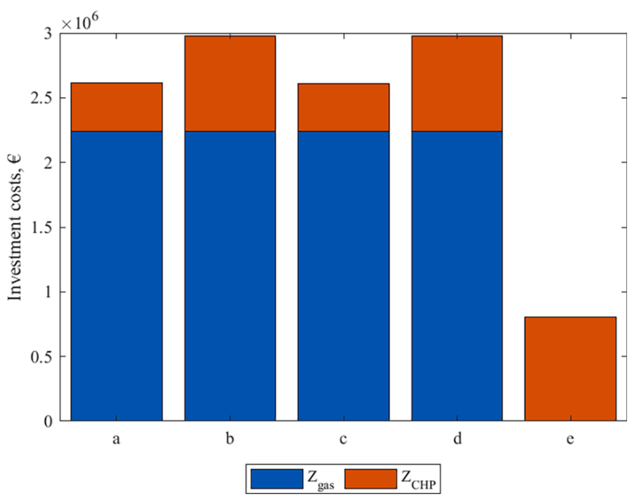


Fig. 15. Investment costs.

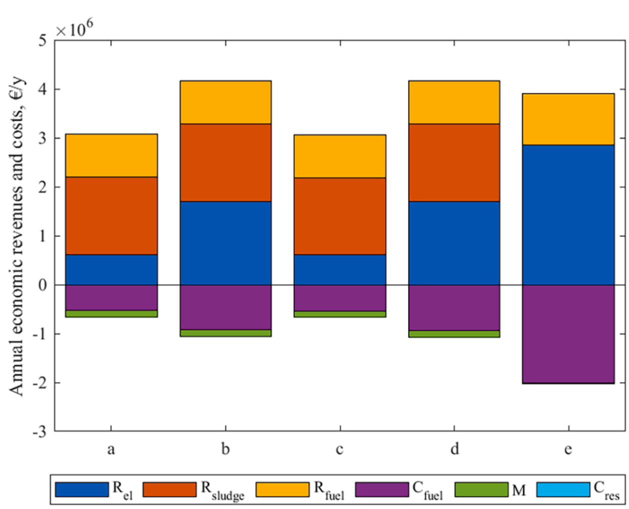


Fig. 16. Annual economic revenues and costs.

variation of methane cost that fluctuates over time. The results of this analysis are shown in Fig. 17, where the variation of SPB with specific costs of sludge disposal and methane for the best cases identified through the previous analysis (a, b, c and d) is reported.

For the sake of comparison, the effect of methane cost fluctuation is assessed also for the conventional solution, Fig. 18.

At the highest specific costs taken into account, the SPB decreases to 1.03 y for the syngas engine and 0.96 y for the dual-fuel configuration. Therefore, even if the proposed solution appears to be economically feasible, its SPB is still higher than the SPB obtained for the conventional solution at the highest specific cost of methane, which is 0.513 y. However, the proposed solution is more environmentally friendly than the conventional one due to the use of waste biomass-derived fuel as indicated by the PER, whose values are illustrated in Fig. 19.

Except for the lowest ER taken into account, the PER of the proposed solution is higher than the one obtained for the conventional solution that is 0.732. Moreover, it is interesting to notice that except for the dual-fuel configuration analyzed at different ERs, the most economically convenient solution corresponds to the one that maximizes the PER. For the sake of completeness, the ranges of variation and the value of gasification temperature and ER in correspondence of which the minimum SPB and the maximum values of NPV and PER are reached are shown in Table 8.

Conclusion

In this paper, the energy and economic analysis of an integrated combined heat and power system based on sewage sludge gasification is proposed. Syngas produced from gasification is used as a fuel in an internal combustion engine for combined heat and power production. Gasification is investigated through sensitivity analyses to identify the temperature and the equivalence ratio that maximize the energy performance of the system. Different solutions are compared to identify the most economically convenient and environmentally-friendly configuration: the internal combustion engine is supposed to be fuelled with syngas or with syngas and methane. The proposed solutions are also compared to a conventional layout based on a cogeneration engine fueled with methane that produces the same amount of thermal energy that is used to supply sludge thermal drying.

The main results of the analysis are reported below.

1. Lower heating value and mass flow rate of syngas are significantly influenced by the equivalence ratio, whereas the process temperature has a slight effect on these parameters. The trend of the lower heating value significantly influences the primary power of syngas that increases with the process temperature and decreases with the equivalence ratio.
2. Considering the cogeneration unit, the dual-fuel operation allows increasing the engine efficiency, especially the electrical one, due to the higher energy content of methane. In terms of electrical energy

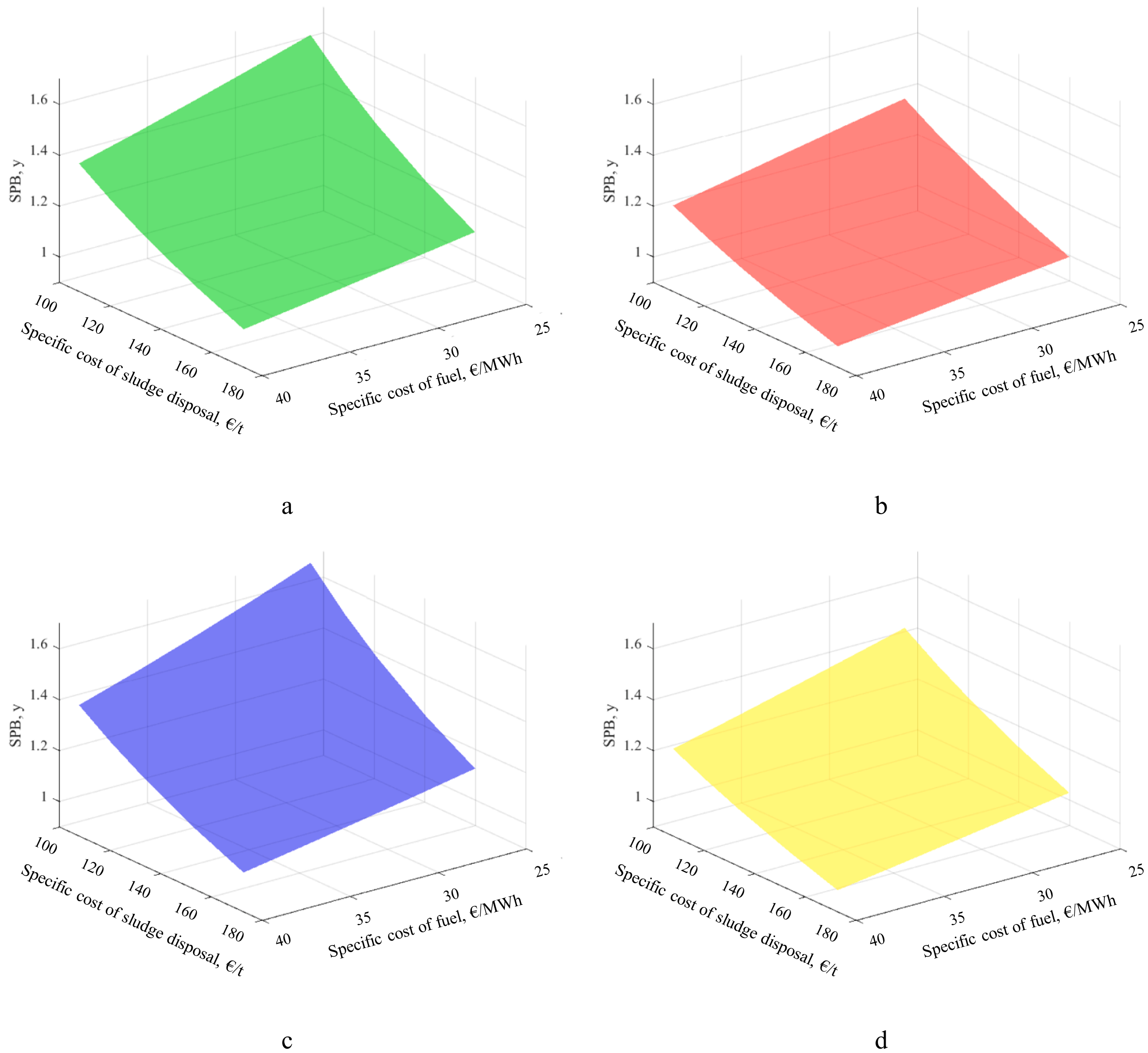


Fig. 17. Variation of Simple Pay Back with specific costs of sludge disposal and methane for the cases a, b, c and d.

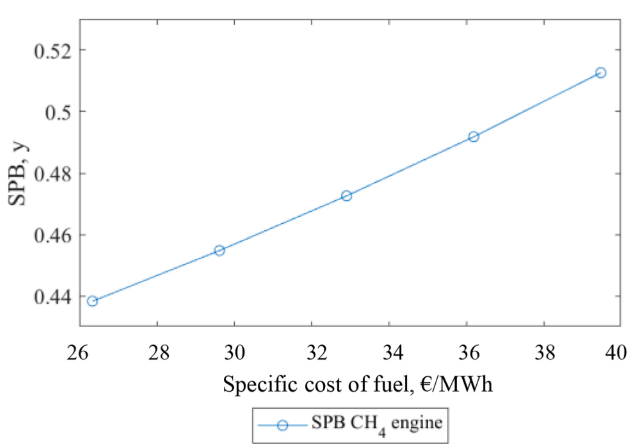


Fig. 18. Variation of Simple Pay Back with the specific cost of methane for the methane engine.

production, the analyzed solutions allow supplying between 9.3 and 10.8% and between 28.8 and 30.7% of the wastewater treatment plant demand when the syngas engine or the dual-fuel engine is used, respectively.

3. From an economical point of view, all the proposed solutions are convenient, with a simple payback period lower than 1.4 years. To take into account the variability of fossil fuels tariff and sludge disposal cost during the last years, the effect of these costs is analyzed finding that the simple payback period of the proposed system could decrease to around 1 year.
4. The use of cogeneration systems is extremely convenient in wastewater treatment plants that require thermal and electrical energy at the same time. Self-production of electrical energy and use of thermal energy for sludge treatment allow a significant reduction of operational costs.

Due to the attractive results, the proposed system will be further analyzed through an exergy approach to assess the exergy destruction and optimize the process to improve its overall thermodynamic efficiency.

CRediT authorship contribution statement

Paola Brachi: Methodology, Software, Validation, Writing – review & editing. **Simona Di Fraia:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Nicola Massarotti:** Resources, Supervision, Funding acquisition, Resources, Supervision,

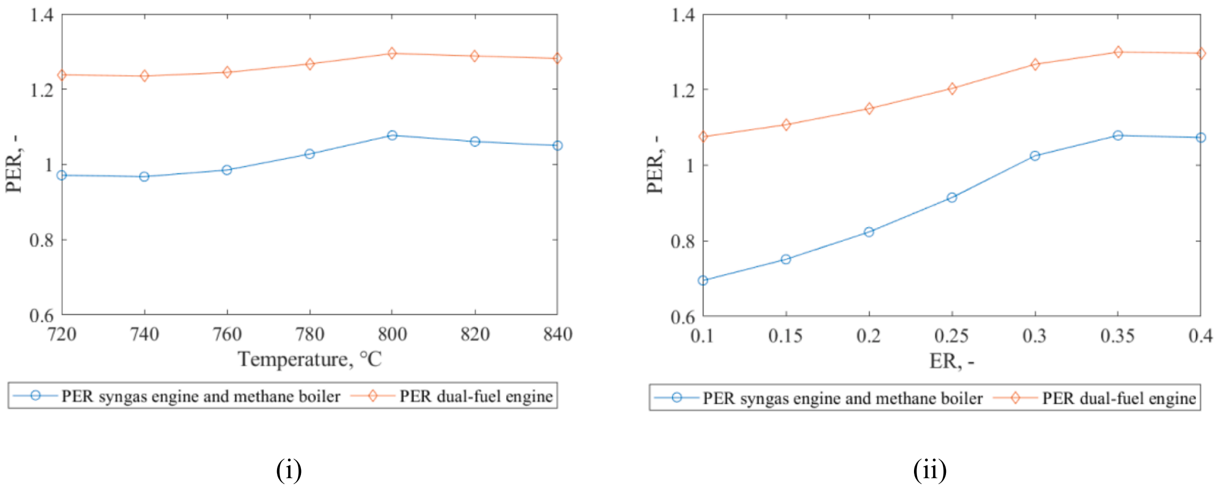


Fig. 19. PER: variation with gasification temperature (i) and ER (ii).

Table 8
Ranges of variation of SPB, NPV and PER for both the analyzed cases.

Case		SPB		NPV, M€		PER	
		Range	Min	Range	Max	Range	Max
Syngas engine	T sensitivity	1.30–1.31	800 °C	21.1–21.6	800 °C	0.967–1.08	800 °C
	ER sensitivity	1.30–1.37	0.35	19.9–2.13	0.35	0.695–1.08	0.35
Dual fuel engine	T sensitivity	1.16–1.17	800 °C	27.8–28.1	800 °C	1.23–1.29	800 °C
	ER sensitivity	1.16–1.19	0.30	27.4–28.0	0.30	1.08–1.30	0.35

Funding acquisition. **Laura Vanoli:** Resources, Supervision, Funding acquisition.

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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