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Economic assessment of an integrated waste to energy system for an urban sewage treatment plant: a numerical approach

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ABSTRACT

The paper investigates the economic investment of an integrated system including different waste to energy technologies for the exploitation of the wastes from an urban sewage treatment plant. In the considered system, the final waste from the purification plant is fed into an anaerobic digester, and the digested sludge is then separated into the solid and liquid fractions. The former is employed as a fuel in a downdraft gasifier, while the latter is purified by means of both forward and reverse osmosis. Finally, the obtained bio-gas and syngas are used in a cogeneration system based on an internal combustion engine to produce electric and thermal power.

The energy conversion performance of the system is evaluated by means of a fully dynamic numerical approach. An ad-hoc library for the simulation of energy conversion systems is developed under the OpenModelica open source platform; the library includes the main components that equip the considered CHP system and they can be connected as they are logically connected in the real plant. Each component is modelled by means of equations and correlations that calculate their performance on a time dependent basis. Furthermore, the library includes the models for the calculation of the investment parameters, such as the cash flow of the plant and the payback time.

Finally, the numerical approach is used for the evaluation of the anaerobic digestion – gasification - water treatment integrated plant for the real case of the city Taormina in Sicily, Italy. The simulation demonstrates that it is possible to decrease the final wastes to landfill by a 73% while producing the 30 % of the electric energy required for the plant operation. Thus, the payback time of the integrated plant results to be lower than 3 years.

Keywords: biomass energy recovery, anaerobic digestion, gasification, water purification, simulation, economic assessment

INTRODUCTION

The attention towards the efficient use of energy sources has increased substantially in the recent years due to the increasing awareness of the limits regarding the fossil fuels. Exploitation of biomasses is not only a promising opportunity but it is a concrete contribution to the energy production. In fact, bioenergy accounts for approximately 10% of world total primary energy supply and the figure is constantly increasing [1]. Focusing on the electric energy production only, the bioenergy still represents an important contribution and in 2012, a total of 370 TWh of bioenergy electricity was produced corresponding to 1.5% of world electricity generation

[2]. Numerous technologies for generating bioenergy heat and power already exist, such as solid wood heating installations for buildings and biogas digesters for power generation as well as large-scale biomass gasification plants are also employed for heat and power generation.
An important mean for increasing the contribution of bioenergy is the development of biomass-based small and micro combined heat and power systems [3], in order to exploit the biomass sources locally. Especially for the small size applications of the CHP systems, the electric and thermal energy requirements of the final user can be very variegated, thus the accurate design of the small size cogeneration system has to account for both the detailed specifications of the addressed case and the transient nature of its energy demand.
Therefore, simulation tools represent an important instrument in the design process of a combined heat and power system optimized for the particular application. Many examples of numerical models for the various individual domains of the energy system can be found in literature, both for energy plants [4, 5] and industrial processes [6] as well as for investigating new energy production concepts [7]. On the other hand, fewer approaches can be found when combining the physics of the real phenomena with the operating strategies and the economic evaluation of the energy systems [8].
In this paper, an ad-hoc library for the simulation of waste-to-energy system including anaerobic digestion and gasification and final water treatment is developed under the OpenModelica open source platform and the model of a small size system is constructed. The sub-models for each component that equips the whole system are derived by means of equations and correlations in order to calculate the system performance on a time dependent basis.
The numerical analysis of the combined waste-to-energy system investigates the amount of energy that can be recovered for the real case of the city water treatment plant in Taormina in Sicily, Italy. The simulation demonstrates that it is possible to decrease the final wastes to landfill by a 73% while producing the 30 % of the electric energy required for the plant operation. Finally, the economic analysis of the combined plant is also address and the calculated payback time of the integrated plant results to be lower than 3 years.

TEST CASE

The analysed combined waste-to-energy system is applied to the residues from the urban sewage treatment plant of Taormina in Sicily, Italy. The considered case study represents an interesting test bench for the predictive capabilities of the developed library, since its biomass throughput is highly time dependent. In fact, even though the inhabitants of the city amount to 11,000 only, the number of tourists is much larger than this figure and varies significantly during the year, see Fig. 1.
Table 1 lists the main operating parameters of the water treatment plant that have been considered in the analysis. In particular, the electric energy requirements have been accounted for in terms of both annual consumption and installed power.

Table 1: Main operating parameters of the water treatment plant considered in the analysis.

Required Electric Power	400	kW
Total Electric Energy Consumption	2,806,940	kWh/y
Total Treated Sewage	5,500,000	m3/y
Disposed Final Residues	1,855	t/y
Final Residues Humidity	28	%

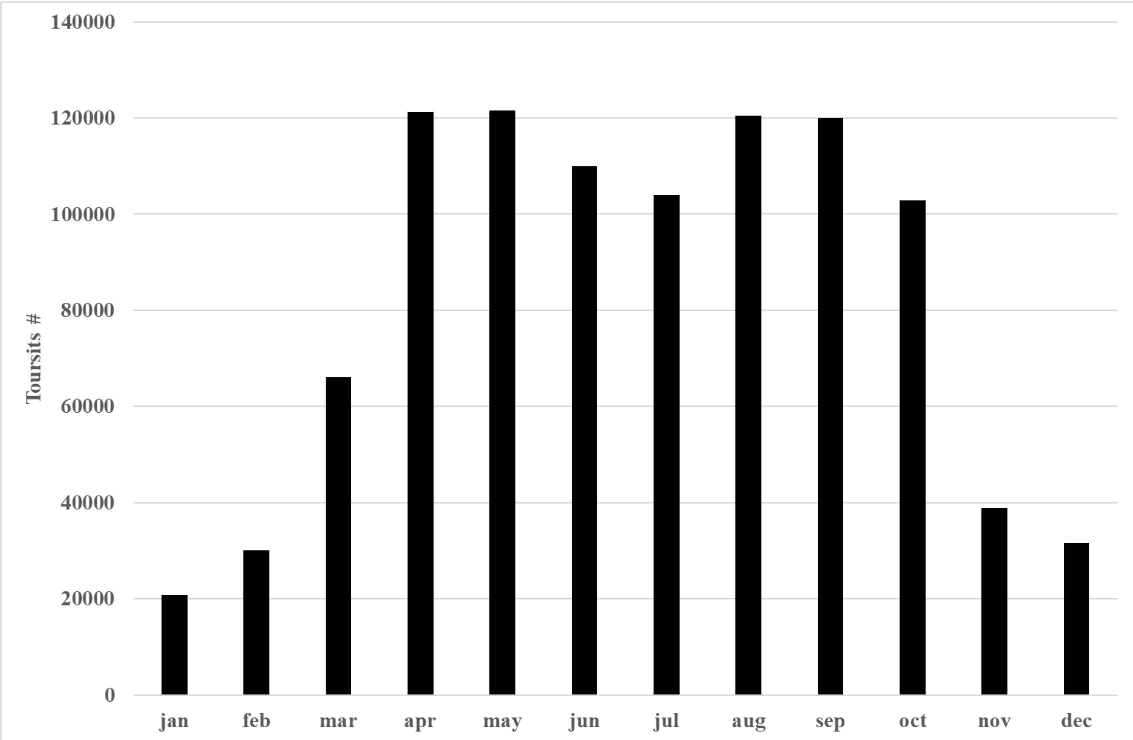

Figure 1: Tourists in Taormina in 2013 [9].

Table 2 reports the main operating costs of the plant and the largest expenses are due to the electric energy purchase and the total cost of the disposal the final residues from the water treatment. This expense amounts to more than 220,000 Euro per year and it is comparable to the cost for electricity. In fact, the annual disposed residues consist of 1,855 t/y and more than 60 lorry transports.

Table 2: Main operating costs of the water treatment plant considered in the analysis.

Electric Energy Annual Expense	337,000	Euro/y
Specific Cost for Final Residues' Disposal	120	Euro/t
Total Cost for Final Residues' Disposal	222,600	Euro/y

Main target of this analysis is the exploitation of the final residues of the sewage treatment plant in order to exploit them as a biomass and a resource instead of a cost for the plant operation.
The proposed system for the conversion of the final residues in energy is the combined anaerobic digestion – gasification – water purification plant plotted in Fig. 2. The employment of the three processes enables to maximize the exploitation of the biomass and to reduce the remaining amount of waste; thus, it is possible to improve the total energy conversion efficiency of the system calculated on the basis of the initial energy content of the adopted biomasses. First, the humid residues from the urban sewage treatment plant is converted into biogas using an anaerobic digester; then, after the time period necessary for the bacterial reactions to take place, the biological sludge is dehydrated and successively dried. The dried part of the sludge is loaded in the gasifier, while the liquid part is treated in the water purification process. Before storing the syngas and the biogas in the tank, a gas treatment system is adopted, including filtration, cooling and desulfurization. The purified gas is then used as fuel in a spark ignition internal combustion engine ICE. An alternator connected with the ICE produces electrical energy while the heat exchanged at high and low temperature is used for self-sustenance operations of the plant such as the heating of the anaerobic digester or the biological sludge

drying. Finally, the liquid fraction of the biological sludge is converted in distilled water and in an ammonia solution after micro, ultra and nano-filtration and finally forward/reverse osmosis treatments.
The gasifier humid slag and the solid part of the filtration are disposed in a landfill in accordance with the local regulation.

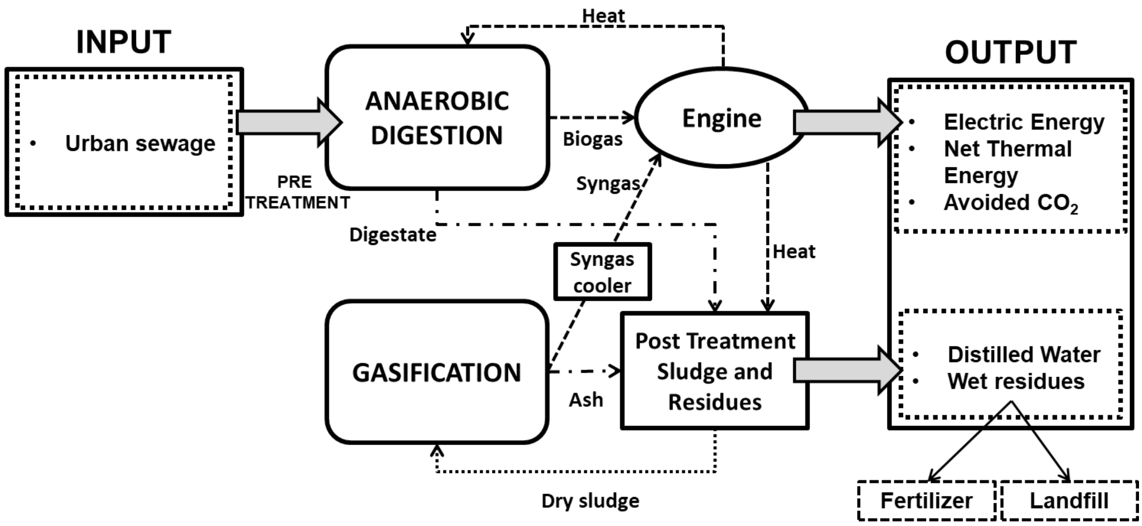

Figure 2: Layout of the considered combined plant.

NUMERICAL MODELING

The lumped parameters library for describing the components of the proposed combined WTE system is created using the Modelica language. The sub-models provided in the library are implemented to be as generic as possible and they simulate the overall performance of the single components. The bond graph approach is adopted for modelling the whole system and the different sub-models are linked via power ports in order to calculate the energy balance [10]. Figure 3 depicts the layout of the final configuration of the combined system including also the models for the initial biomass input. In the following, the numerical models constructed for the main components of the analysed system are described more in detail.
The performance of the internal combustion engine CHP unit is calculated on the basis of the operating control strategy for the load variation. In the real plant, the internal combustion engine load is held constant at a reference value except for few stops due to maintenance. According to the load profile the engine power output and fuel consumption are calculated as follows:

$$P_{ICE,EL} = \frac{Load_{ICE}}{100} P_{ICE,EL,MAX} \tag{1}$$
$$P_{ICE,TH} = \frac{Load_{ICE}}{100} P_{ICE,TH,MAX} \tag{2}$$
$$\dot{m}_{ICE,f} = \frac{P_{ICE,EL}}{c_{ICE,s}} \tag{3}$$
$$\eta_{ICE,EL} = \frac{1}{c_{ICE,s} \cdot LHV_f} \tag{4}$$

The engine electric energy conversion efficiency is determined by the specific fuel consumption obtained from the operating map of the CHP unit provided by the manufacturer, see Fig 4. The map is implemented into the engine model and the value of the engine torque output is then corrected on the basis of the Lower Heating Value, LHV, of the biogas and syngas produced by the combined system.

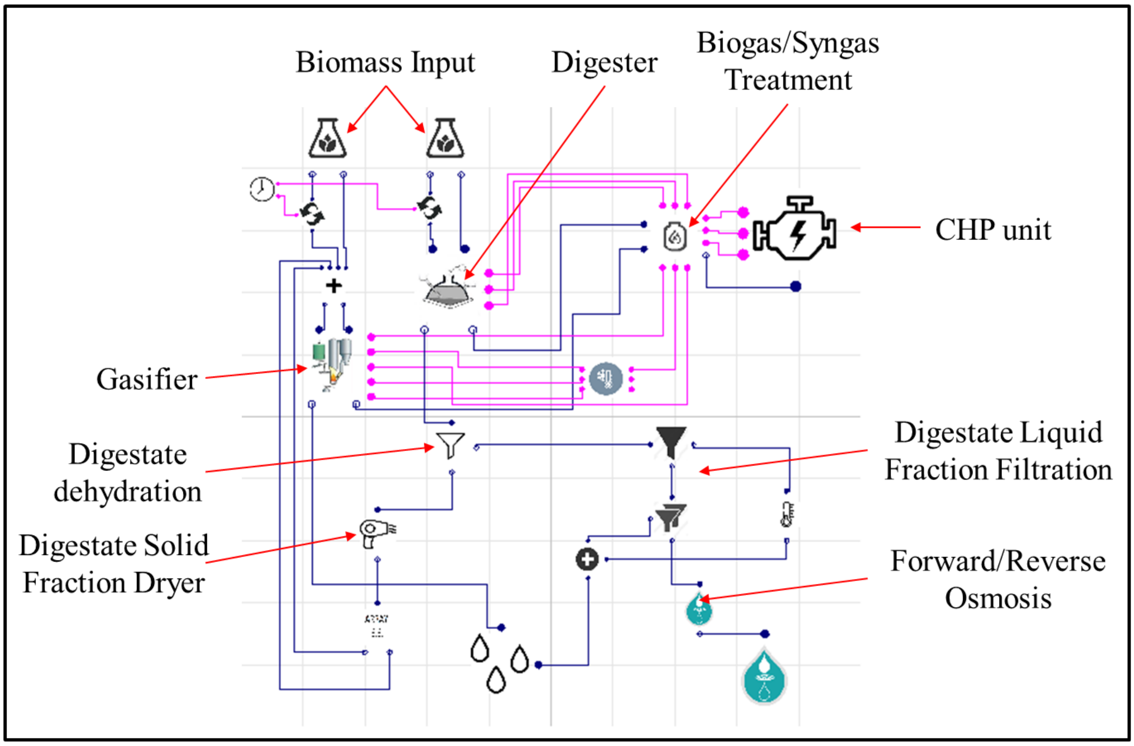

Figure 3: Numerical model layout of the considered combined plant.

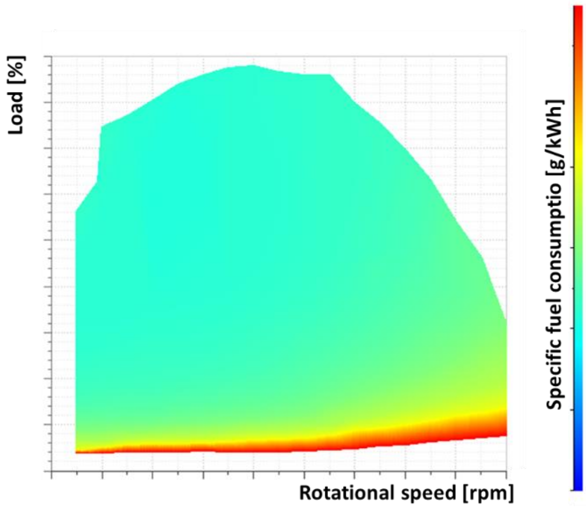

Figure 4: Internal combustion engine operating map

The numerical models for the simulation of the performance of the considered biomass conversion processes are described and validated previous works [11, 12]. In particular, the anaerobic digestion process is evaluated by means of global expressions which correlate the biomasses used as an input to the digester and the equivalent yield of biogas. The characteristics in terms of moisture, ashes, volatile matter and lignin content are estimated for each biomass on the basis of a compositional database calculated by means of proximate analysis. In particular, the total solid is assumed as the sum of two macro-species: volatile matter and inert ashes. Only a part of the volatile matter is biodegradable and it is calculated by means of the empirical expression developed by Chandler et al. [13]. By means of the ultimate and proximate

analysis of the biomass adopted for the anaerobic digestion the volatile matter is estimated as well as the carbon and hydrogen contents are evaluated. Thus, the biogas yield and its composition are calculated by means of a global reaction [14], which accounts for the main bacterial reactions that occur in the reactor (i.e. hydrolysis, fermentation, acetogenesis and methanogenesis subdivided into acetoclastic and hydrogenotrophic phases) [15]. A purification treatment for the biogas is accounted for in order to remove solid or dangerous components for the combustion, such as H2S, by means of after treatment devices. The effect of these after-treatments is considered in the simulation by varying the biogas composition accordingly.
Similarly, the gasification process is also evaluated by means of global expressions, which correlate the biomasses used as an input to the gasifier and the equivalent yield of syngas. A more throughout description of the model can be found in [12]. The initial biomass Higher Heating Value (HHV) is calculated by means of the Boie equation, while the thermodynamics properties, such as the specific heat, entropy and enthalpy of formation, are estimated using the NIST database [27]. The composition of the initial biomass is accounted for using the ultimate analysis; thus, the biomass is assumed as a single component fuel (CnHmOpNqSr) with no moisture. The contribution of moisture, i.e. of the initial water content, is calculated separately, considering also the drying process [17]. The gasification reactions are modelled using a single global reaction at chemical and thermodynamic equilibrium [18]. The adopted thermochemical model assumes two important hypotheses. First, the residence time of the reactants is supposed to be high enough to reach chemical equilibrium. Secondly, it is assumed that all the carbon in the biomass is gasified, and thereby, the formation of charcoal can be neglected. The validity of these two assumptions varies significantly on the basis of the considered gasifier as well as of the biomass used. The present work is referring to a downdraft gasifier, which is usually characterized by long residence time, thus the first assumption can be acceptable. The second hypothesis is more limiting, in particular when considering a number of different biomass. The effect can be summarized in an overestimation of the producer gas efficiency. Furthermore, it two additional equations that take place in the gasification zone are included in the modeling: the methane reaction and the water-gas shift reaction [19].
Assuming that all species behave as ideal gases and all reactions develop at ambient pressure, the equilibrium constants are calculated as a function of the composition of the producer gas by using the standard Gibbs energy. Finally, the equilibrium temperature at which the reactions take place is calculated by means of an iterative procedure using a chemical and thermodynamic convergence algorithm. Not-ideal behaviours such as wall heat transfer through the boundary of the combustion chamber are also considered in this algorithm.
The numerical model is able to predict the syngas main characteristics: yield, Lower Heating Value (LHV), flow rate, composition in terms of CO, CO2, H2, CH4, H2O, N2, SO2 and the equilibrium temperature of the reaction [17].
The calculated reduction of the final residues to be disposed and the amount of purchased electric energy are finally employed for the calculation of the investment parameters of the energy system. In particular, the net present value (NPV) is calculated on the basis of the weighted average cost of capital (WACC).

$$C_0 = -Inv \tag{5}$$
$$C_i = -C_{tot,en_i} + R_{net\_met_i} + S_i \tag{6}$$
$$NPV = \sum_{i=0}^{Years} \frac{C_i}{(1+wacc)^i} \tag{7}$$

The values of the cash flow are evaluated by considering the savings in terms of reduced cost for the transport and disposal of the sewage residues and the and electric energy that has still to be purchased with reference to the original configuration of the water treatment plant.

RESULTS

The numerical model described in the previous section is used for calculating the performance of the combined anaerobic digestion – gasification – water purification system over a one-year operation of the sewage treatment plant of Taormina. The final residues from the sewage treatment process have been available for the year 2013 and they follow the trend of the tourists flow as shown in Fig. 1. Therefore, the biomass input for the combined system is varied accordingly and Figs. 5 and 6 plot the results in terms of monthly electric energy and thermal energy production. Fig. 6 shows also the contribution to the heat recovery of the oil and cooling systems at low temperature, i.e. approximately at 70 °C, and the one of the exhaust gases at high temperature, i.e. approximately at 150 °C.

Table 3 reports the annual yield of the analysed system in terms of main outputs. It can be noticed that the syngas production is remarkable and it is comparable to the biogas yield. Therefore, the electric and thermal energy production of the plant is depending considerably from the syngas operation. The size of the CHP unit is close to 100 kW, which is close to 25% of the total electric power installed for the sewage treatment plant's requirements. Table 3 as well as Fig. 5 depict the net electric energy production since the electricity consumption of the combine plant is already taken into account. Conversely, the system output in terms of thermal power output is almost completely employed for the regular operation of the proposed plant; the sludge drying for the gasifier and the anaerobic reactor heating are the main processes that consume the thermal energy recovered from the CHP unit.

Along with a significant amount of energy produced, the system purifies a noteworthy amount of water that can be reused in the sewage treatment plant or sold as demineralized water.

Finally, the residues remaining at the end of the combined system are calculated to be less than one third of the initial quantity. Thus, the waste that has to be disposed is definitely lower with an important reduction in the total cost the final residues disposal.

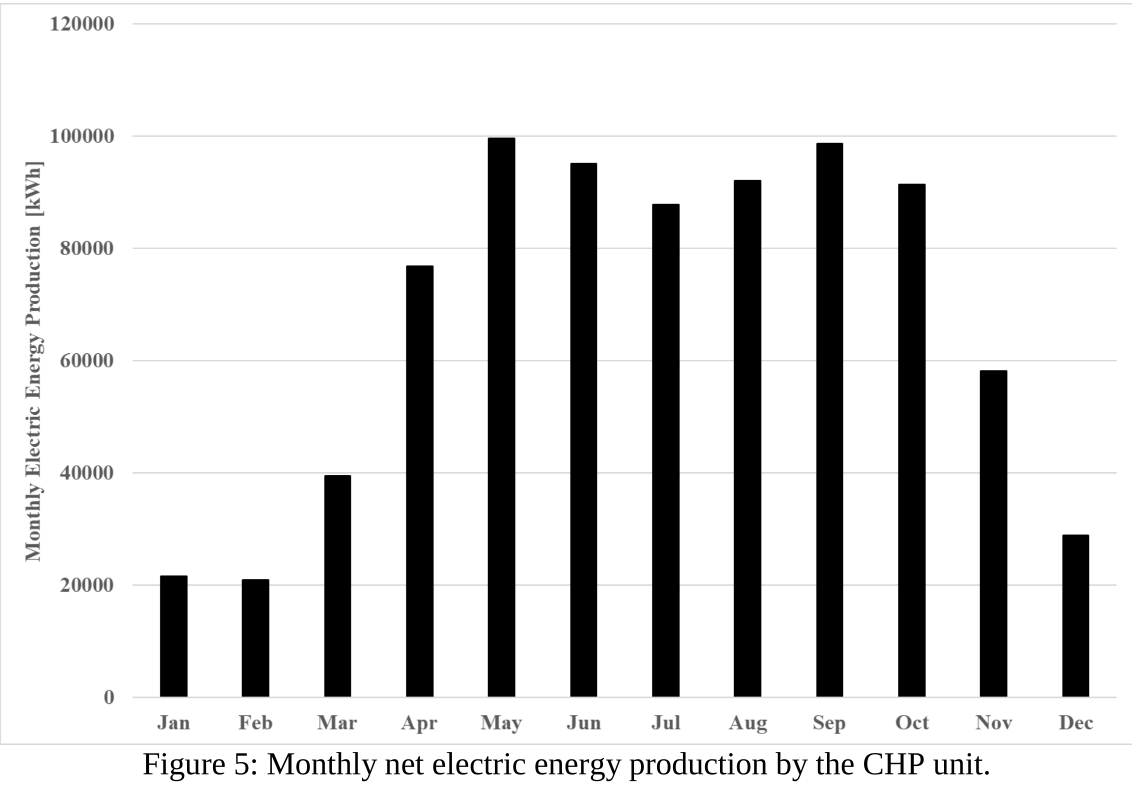

Figure 5: Monthly net electric energy production by the CHP unit.

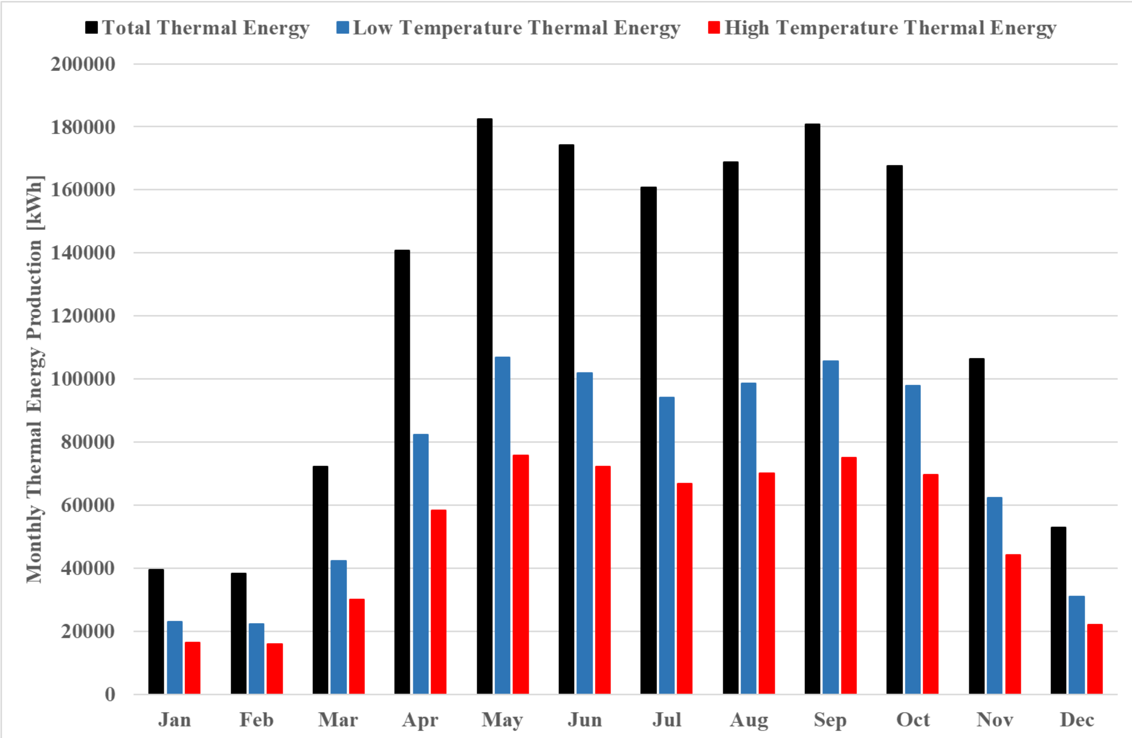

Figure 6: Monthly gross thermal energy production by the CHP unit.

Table 3: Main outputs of the combined plant.

Biogas Yield	371	t/y
Syngas Yield	315	t/y
CHP Electric Power	92.4	kW
Total Net Electric Energy Production	809,710	kWh/y
Total Gross Thermal Energy Production	1,484,472	kWh/y
High Temperature Thermal Energy Production	868,416	kWh/y
Low Temperature Thermal Energy Production	616,056	kWh/y
Demineralised Water	1,900	t/y
Disposed Final residues	514	t/y

The economic assessment of the proposed combined anaerobic digestion – gasification – water purification system is investigated by comparing the energy expense of the proposed plant with the case in which the entire electric energy consumption is purchased and the remaining residues are totally disposed to landfill. Table 4 reports the savings that can be obtained from the CHP unit due to the reduced amount of electric energy purchased and to the reduced expense for the residues' disposal. In fact, even though the avoided cost from the electric energy purchase is remarkable, the savings for the lower amount of wastes to landfill is larger and contribute substantially to the profitability of the investment.

Nevertheless, the main profit of the proposed combined plant is due to the feed-in tariff granted by the Italian legislation for the electric energy production from renewable sources. The sum of the above-mentioned avoided costs amounts to approximately to the revenues from the incentives of the bioenergy production from biomasses. In the evaluation of the system revenues no net energy metering is accounted for, i.e. $R_{net\_met_i} = 0$.

Table 4: Main revenues and avoided costs of the combined plant.

Revenues from Feed-in Tariff	259,107	Euro/y
Avoided Cost from Electric Energy Purchase	97,300	Euro/y
Avoided Cost from Final Residues Disposal	161,000	Euro/y

For the NPV calculation, a capital cost for the proposed combined plant equal to 1,350,000 Euro is considered. Figure 6 shows the trend of the calculated NPV over a simulation of 10 years. Main assumption of this calculation is that the energy requirements are considered constant for each year and equal to the reference values of Table 1. Under this hypothesis, the payback time lies between the second and third year and the final revenue is larger than 4.3 Million Euro, which is approximately three times the initial investment. This figure could be further improved if the revenues from the demineralised water were taken into account.

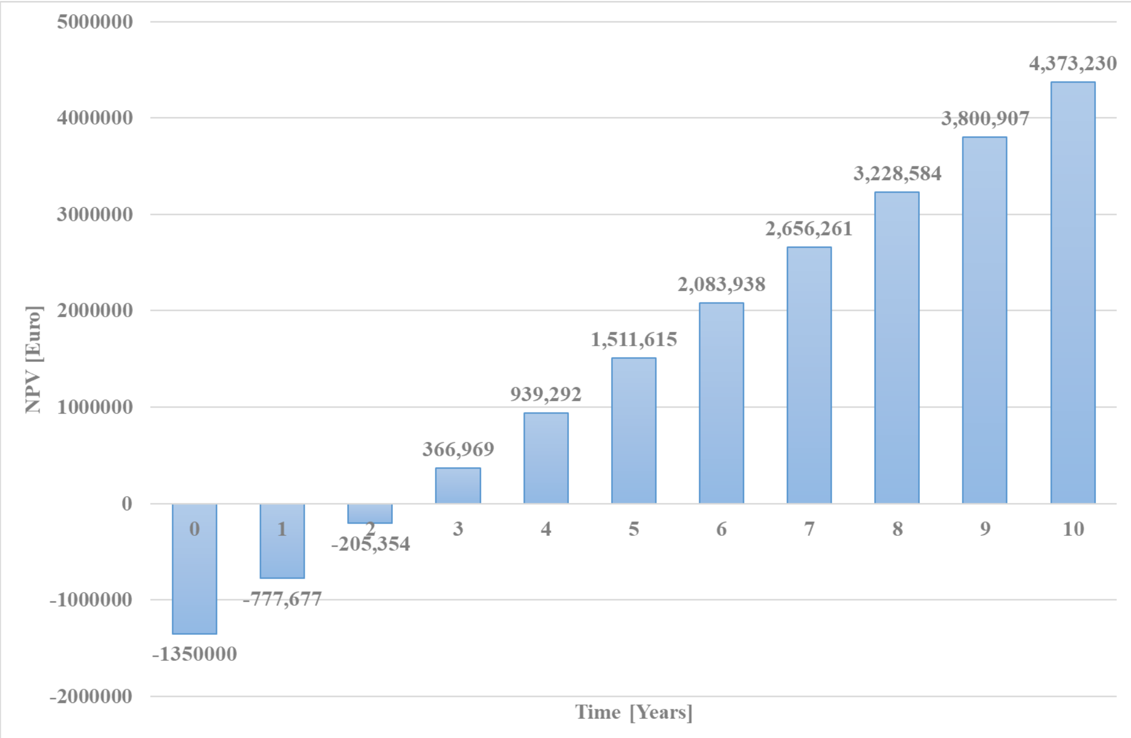

Figure 6: NPV calculation for the proposed combined plant.

CONCLUSION

In this paper, the benefits of the employment of a combined anaerobic digestion – gasification – water purification system to the Taormina sewage treatment plant have been highlighted. A time-dependent OpenModelica numerical library has been constructed and the energy conversion performance and economics assessment of the proposed plant have been calculated. The simulation demonstrated that the biogas and syngas yield were sufficient to fuel a 100 kW CHP unit, which represented the 25 % of the total electric power installed in the considered plant. Therefore, the net electric energy production resulted to be a remarkable amount compared to the total electricity consumption, while the recovered heat was almost completely employed for the heating of the anaerobic digester and the sludge drying for the gasifier. Furthermore, the final residues to be disposed reduced to less than one third with respect to the total amount to landfill without their exploitation in the combined system.
Finally, the net present value of the investment was calculated over a period of 10 year assuming an initial capital cost of the combined plant equal to 1.35 MEuro. The revenues of the proposed

combined plant were calculated on the basis of the feed-in tariff for the bioenergy production according to the Italian regulation for the electric energy production from biomasses. Furthermore, the avoided costs were calculated in terms of savings for the electric energy purchase and for the reduced amount of residues to be disposed. The avoided costs resulted to be similar to the revenues from the bioenergy production's incentives. Thus, the simulation demonstrated that the payback time was lower than three years and the final revenue larger than 4.3 Million Euro.

Nomenclature

C_0	Cash flow at the zero-th year, Euro
CHP	Combined Heat and Power
C_i	Cash flow at the i-th year, Euro
$c_{ICE,s}$	ICE specific fuel consumption, $\frac{g}{kWh}$
C_{tot,en_i}	Total energy cost for the i-th year, Euro
ICE	Internal Combustion Engine
Inv	Initial investment, Euro
LHV_f	Fuel lower heating value, $\frac{MJ}{kg}$
$Load_{ICE}$	ICE load, %
$\dot{m}_{ICE,f}$	ICE fuel consumption, $\frac{kg}{s}$
NPV	Net Present Value, Euro
$P_{ICE,EL}$	ICE electric power output, kW
$P_{ICE,EL,MAX}$	Maximum ICE electric power output, kW
$P_{ICE,TH}$	ICE thermal power output, kW
$P_{ICE,TH,MAX}$	Maximum ICE thermal power output, kW
$R_{net\_met_i}$	Revenue from the net metering at the i-th year, Euro
S_i	Savings from the original energy cost at the i-th year, Euro
$WACC$	Weighted average cost of capital, -

Greek symbols

$\eta_{ICE,EL}$	ICE electric energy conversion efficiency, -

References

1. IEA, (2014), Heating without Global Warming - Market Developments and Policy Considerations for Renewable Heat, OECD/IEA, Paris.
2. IEA, (2015), Medium-Term Renewable Energy Market Report 2015, OECD/IEA, Paris.
3. R. Beith, Small and Micro Combined Heat and Power (CHP) Systems, 2011 Woodhead Publishing Limited, Cambridge
4. H. Asgari, M. Venturini, X. Chen, R. Sainudiin, "Modelling and Simulation of the Transient Behaviour of an Industrial Power Plant Gas Turbine", J. of Engineering for Gas Turbines and Power, 2014, Vol. 136, pp 1-10.
5. M. Bianchi, L. Branchini, A. De Pascale, A. Peretto, "Application of environmental performance assessment of CHP systems with local and global approaches", J. of Applied Energy, 2014, Vol. 130, pp 774-782.
6. D. Bottazzi, S. Farina, M. Milani, L. Montorsi "A numerical approach for the analysis of the coffee roasting process", J. of Food Engineering, 2012 Vol. 112 (3), pp 243-252.

7. M. Milani, L. Montorsi, F. Paltrinieri, M. Stefani, "Experimental and numerical analysis of the combustor for a cogeneration system based on the aluminum/water reaction", J. of Energy Conversion and Management, 2014, Vol. 87, pp 1291-1296.
8. P. Palensky, E. Widl, A. Elsheikh, "Simulating Cyber-Physical Energy Systems: Challenges, Tools and Methods". IEEE transaction on systems, man, and cybernetics: systems, 2014, Vol. 44 (3).
9. Italian Statists Institute, "Elaborazioni dell'Osservatorio Turistico su dati ISTAT", 2013.
10. W. Borutzky, B. Barnard, J.U. Thoma, "Describing bond graph models of hydraulic components". J. of Mathematics and Computers in Simulation, 2000, Vol. 53, pp 381–387
11. M., Milani, L., Montorsi, M., Stefani, An integrated approach to energy recovery from biomass and waste: Anaerobic digestion–gasification–water treatment, Waste Management & Research, Vol. 32, No. 7, pp 614-625, 2014.
12. M., Milani, L., Montorsi, M., Scolari, Energy Recovery from Waste by Means of a Gasification System: Numerical Approach, Proceedings of Third International Conference on Applied Energy, Perugia, Italy, May 16-18, 2011, pp 1555-1568.
13. J. A. Chandler, W.J. Jewell, , J.M. Gosset, P. J. Vansoest, B.J. Robertson, Predicting methane fermentation biodegradability, Biotechnology and Bioengineering Symposium, Vol. 10, pp. 93-107, 1980.
14. M. Kayhanian,G. Tchobanoglous, R. C. Brown, Biomass conversion process for energy recovery, Handbook of Energy Conservation and Renewable Energy, CRC Press Taylor & Francis Group, 2007.
15. J. Biswas, R. Chowdhury, P. Bhattafcharya, Mathematical modeling for the prediction of biogas generation characteristics of an anaerobic digester based on food vegetable residues, Biomass & Energy, Vol. 32, pp. 80-86, 2007.
16. M.W. Jr Chase, C.A. Davies, J.R. Jr Davies, D.J. Fulrip, R.A. McDonald, A.N. Syverud, JANAF thermochemical tables, Journal of Physical Chemistry, Vol. 14, Supp1, 1985.
17. Z.A., Zainal, R., Ale, C.H., Lean, K.N., Seetharamu, K.N., Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials, Energy Conversion and Management, Vol.42, pp. 1499-1515, 2001.
18. A. Melgar, J. Perez, H. Laget, A. Horillo, Thermochemical equilibrium modeling of a gasifying process, Energy Conversion and Management, Vol.48, pp.59-67, 2007.
19. C. Higman, M. Van den Burg, Gasification, Elsevier, 2008.