A circular approach for the management of biogas flows from sewage sludge

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Abstract: Sewage sludge is considered one of the most critical resources to be managed in the urban context for the transition toward a circular economy. If the one hand, the sewage sludge includes potentially dangerous components to human health and ecosystems; on the other hand, it is rich in nutrients and valuable materials (e.g., phosphorus, nitrogen, etc.), allowing to ensure an energetic production comparable with traditional fuels. Therefore, it is recommended to adopt treatments to reduce the hazardous contaminants recovering energy and matter from sewage sludge. For this scope, the anaerobic digestion treatment is one of the most adopted processes. It allows the biological stabilisation of the treated sludge mass and, at the same time, the recovery of matter (i.e., digestate production) and energy (i.e., biogas production), in total compliance with a circular economy perspective. The biogas produced can be used for various purposes (e.g., electricity production, grid connection, refilling of vehicles, etc.). To identify the best environmental alternative, it is necessary to analyse the chemical and physical characteristics of the biogas, strictly related to features of the sewage sludge adopted as input on anaerobic digestion treatment. To this concern, the objective of the present work was to develop an analytical model that, starting from the physic-chemical characteristics of the sewage sludge to be treated, allows predicting the composition of the biogas and then identifies the most effective utilisation under an environmental perspective. The model developed was applied to the case of sewage sludge produced in the metropolitan city of Bari, southern Italy. The results show the model's effectiveness in suggesting the most eco-friendly utilisation of the biogas produced starting from the physic-chemical characteristics of the sewage sludge.

Keywords: circular economy, energy recovery, anaerobic digestion, biogas, sewage sludge.

I. INTRODUCTION

Sewage sludge (SS), i.e., the main by-product of wastewater treatment (WWT), is considered one of the most critical resources to be managed in the urban context for the transition towards a circular economy (CE) [1]. Although, it includes dangerous contaminants, both organic and inorganic, and pathogens (i.e., bacteria, viruses, protozoa, etc.) [2]. It is rich in valuable nutrients like nitrogen and phosphorous; the latter is also classified as a critical raw material, i.e., it is estimated to be exhausted in the next 50–100 years [3]. Moreover, at 6% moisture content and 65% organic matter, the SS shows a lower calorific value of about 13.5 kJ/kg [4]. Under this condition, the SS can be considered a solid fuel [5], since its lower calorific value is comparable to traditional fuels' characteristic value, such as lignite and other biomasses. The global climate change, energy crises, and continued population growth, 2,5 billion people expected to live in the cities in 2050 [6] are currently forcing the valorization of the limited resources on earth, introducing more eco-friendly approaches [7]. Under this perspective, the SS must be managed as a key resource. Therefore, it is recommended to adopt treatments to reduce the number of hazardous contaminants and, at the same time, recover energy and matter from this resource. One of the principal treatments addressing this purpose is anaerobic digestion (AD). It is based on a biological fermentation process that occurs in an anoxic environment to chemically stabilise the organic matter contained in the SS. Two main byproducts, biogas and digestate, are recovered from the AD treatment. There are two options to recover the SS in the scientific literature: Sludge-to-Matter (StM) and Sludge-to-Energy (StE). The digestate contains 2.8 g of nitrogen and 0.43 g of phosphorus per kg on a dry basis [8]. StM recovery options allow using the digestate as a soil amendment or fertiliser. In the alternative, StE recovery options consist of valorising the other by-product of AD, i.e., biogas. It is composed of 60–67% methane, 30–33% carbon dioxide, 1–2% hydrogen and 0.5% nitrogen by volume [9]. Generally, biogas is adopted to produce electricity and heat due to significant shares of methane. Or in the alternative, it is purified for the production of biomethane, also known as “renewable natural gas” [10]. Therefore, biogas can be classified as a renewable energy source. SS stabilization through AD has a dual relevance, in total compliance with a CE perspective. Primarily, it allows for removing contaminants and stabilizing the SS. Secondary, it allows reintroducing the biogas into the economic cycle. According to [11], the EU-12 annual production of the SS has increased by almost 50% in the last fifteen years, i.e., from 9.8 million tons in 2005 to over 13 million tons in 2020. From this perspective, the continuous increase in the volume of SS produced represents a benefit for energy and biomethane production, ensuring an increasing availability of alternative raw materials to fossil fuels. In 2018, two-thirds of the global annual biogas production was used to generate electricity and heat, while a relatively small share was upgraded to biomethane [12].

In the last years, many research works investigated solutions and methods to improve the efficiency of the cogeneration unit. In [13] a solution to use the heat rejected from the co-generator to feed a drying system reducing the moisture content of the digestate, was proposed. Currently, biomethane production is generating increasing interest. Many policymakers promote biomethane production to be injected into the natural gas grid [14]. Recent studies investigated the introduction of an upgrading unit into an existing AD plant to convert biogas into biomethane. Consistent with these studies, the energy produced from the AD plant and upgrading unit is greater than the energy required by the processes [15]. In [16] the feeding conditions of the AD process for maximizing biomethane production were investigated. In the previous studies, different models to predict the amount of biogas, biomethane and electricity obtainable from AD treatment were developed, aiming to support the selection of the best recovery alternative to be adopted. In [17] a model is proposed for estimating biomethane production by considering different input substrates (different from SS) and evaluating the environmental impact of the AD and biogas upgrading system. Similarly, a numerical model is developed in [18] to assess an AD plant's emissions and energy consumption with a cogeneration unit and an upgrading unit. In [19] a machine learning algorithm was developed to forecast biomethane production. In [20] the economic convenience ensured by biomethane production was assessed. The simulation environments allow providing a reliable prediction of energy spent [21] and emission factor referred to complex real case studies [22]. A comparison from an environmental perspective between biomethane production and electricity production using biogas obtained by AD of the organic fraction of municipal solid waste is developed in [23]. Nevertheless, if the economic and environmental evaluation of biomethane and energy production from biogas was already investigated, there is a research gap in developing decision-making models allowing to identify the best biogas recovery option by considering the physic-chemical characteristics of the SS feeding the AD treatment. They indeed affect the composition of the biogas and lead to identify the more sustainable recovery option (i.e., generate electricity or generate heat), from an environmental perspective. To this concern, the objective of the present work consists of developing an analytical model that, given the physic-chemical characteristics of the SS to be treated, predicts the composition of the obtainable biogas to identify the most sustainable recovery option in environmental terms. The model was applied to a real full-case study, considering one of the largest wastewater treatment plants (WWTPs) in the metropolitan city of Bari (southern part of Italy).

The rest of the paper is organised as follows: in section II, the three recovery options considered are described in detail, and the analytical model is introduced. Section III presents and discusses the results achieved from the model application. Finally, section IV provides conclusions and insights for future developments of the present research work.

II. MATERIAL AND METHODS

The considered system consists of an AD plant fed by SS with well-known physic-chemical characteristics. From the AD process, biogas with a specific composition is obtained. It can be employed in a generator for electricity production, or it can be treated within an upgrading unit to produce biomethane for feeding into the grid. The developed analytical model allows identifying the most sustainable among three biogas recovery options, assumed as three different scenarios (Fig. 1):

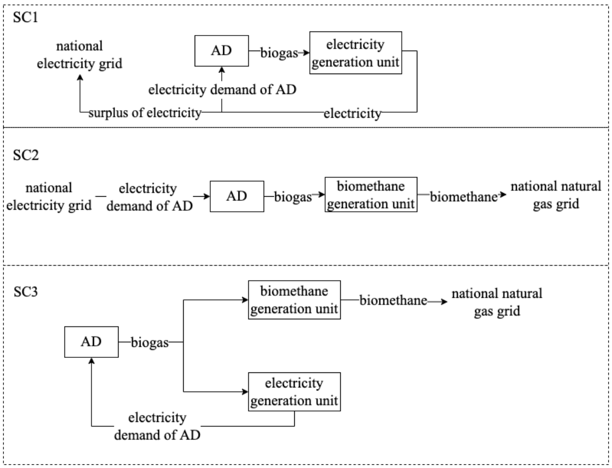

Fig 1. Scenarios considered in developing the analytical model

- Scenario 1 (SC1): the entire amount of biogas produced is used to produce electricity. Firstly, the produced energy is adopted to meet the AD plant's energy demand and, if produced in excess, to feed the grid. In this scenario, the avoided emissions depend on the electricity surplus produced.
- Scenario 2 (SC2): the entire amount of biogas produced is used to produce biomethane by adopting a dedicated upgrading unit. The produced biomethane is adopted to feed the grid. In this scenario, the national electricity grid generates emissions to meet the AD plant's electricity demand and the upgrading unit. The avoided emissions depend on the amount of biomethane produced.
- Scenario 3 (SC3): the entire amount of biogas produced is used to produce biomethane and electricity. The electricity to meet the energy

demand of the AD is produced. The excess biogas is sent to the upgrading unit to produce biomethane adopted to feed the grid. In this scenario, the avoided emissions depend on the amount of biomethane produced. No emission due national electricity grid is considered since the electricity demand of the AD plant, and the upgrading unit is ensured by the same system.

In all cases, the so-called "opportunity emissions" were considered. They are the loss of avoided emission corresponding to other scenarios when one scenario is chosen. For all scenarios, the emissions were estimated as [$kgCO_{2eq}$/day], and the model suggests the scenario ensuring the lower emission value.

The total mass of SS (m_{ss}) feeding the AD treatment is estimated (eq.1).

$$m_{ss} = m_l + TS \left[\frac{g}{day}\right] \quad (1)$$

Where m_l [g/day] is the liquid content of the sludge mass, and TS [g/day] is the total solids content, identified in equation 2:

$$TS = VS + m_{in} \left[\frac{g}{day}\right] \quad (2)$$

Where VS [g/day] is the mass content of volatile solids (i.e., organic matter) and m_{in} [g/day] is the mass of inert matter in the sludge (i.e., inorganic matter). It is assumed that VS is entirely composed of Carbon, Hydrogen, Oxygen, Nitrogen and Sulphur. Given the weight percentages of each element in the influent mass [%wt. VS] (i.e., C%, H%, O%, N% and S%), the molecular formula of the input organic matter is $C_aH_bO_cN_dS_e$ [mol]. Where the indexes (i.e., a, b, c, d, and e) can be estimated by equations 3-7, assuming the molar weight of each element (mol.wt. [g/mol]).
Given the composition of input organic matter, it is possible to estimate the biogas composition analytically using the Buswell model (eq. 8) [24]. This model assumes that the total mass of volatile solids is biodegraded and that water is consumed.

$$a = \frac{C\%}{mol.wt.C} \text{ [mol]} \quad (3)$$

$$b = \frac{H\%}{mol.wt.H} \text{ [mol]} \quad (4)$$

$$c = \frac{O\%}{mol.wt.O} \text{ [mol]} \quad (5)$$

$$d = \frac{N\%}{mol.wt.N} \text{ [mol]} \quad (6)$$

$$e = \frac{S\%}{mol.wt.S} \text{ [mol]} \quad (7)$$

$$C_aH_bO_cN_dS_e + n_{H_2O}H_2O \rightarrow n_{CO_2}CO_2 + n_{CH_4}CH_4 + n_{NH_3}NH_3 + n_{H_2S}H_2S \text{ [mol]} \quad (8)$$

Where the stoichiometric coefficients of the composition of H_2O, CO_2, CH_4, NH_3, and H_2S are estimated in equations 9-12, respectively.

According to the Buswell model’s assumptions, the percentage of methane and carbon dioxide (%CH_4 and %CO_2) theoretically obtainable in the biogas with a biodegradation efficiency η of 100% is provided by equations 14 and15.

$$n_{H_2O} = \frac{1}{4} \cdot (4a - b - 2c + 3d + 2e) \text{ [mol]} \quad (9)$$

$$n_{CO_2} = \frac{1}{8} \cdot (4a - b - 2c + 3d + 2e) \text{ [mol]} \quad (10)$$

$$n_{CH_4} = \frac{1}{8} \cdot (4a + b + 2c - 3d - 2e) \text{ [mol]} \quad (11)$$

$$n_{NH_3} = d \text{ [mol]} \quad (12)$$

$$n_{H_2S} = e \text{ [mol]} \quad (13)$$

$$\%CH_4 = \frac{n_{CH_4}}{n_{CO_2} + n_{CH_4} + n_{NH_3} + n_{H_2S}} \quad (14)$$

$$\%CO_2 = \frac{n_{CO_2}}{n_{CO_2} + n_{CH_4} + n_{NH_3} + n_{H_2S}} \quad (15)$$

The AD process doesn’t allow degrading the whole mass of VS in the SS to be treated; it is necessary to assume a degradation efficiency of the organic carbon η<100%, depending on the AD process parameters (e.g., temperature, pH, etc.). Therefore under this condition, Banks claims that the predicted volume of methane (CH_{4_v}) depends on the application of the Buswell model with a carbon balance [25]. This approach makes it possible to identify the amount of carbon converted into biogas (C_{deg}) (eq. 16).

$$C_{deg} = \%C \cdot \eta \left[\frac{g}{day}\right] \quad (16)$$

Similarly, the amount of carbon converted into methane ($C_{deg_{CH_4}}$) is shown in equation 17.

$$C_{deg_{CH_4}} = C_{deg} \cdot \%CH_4 \left[\frac{g}{day}\right] \quad (17)$$

The corresponding weight of methane (CH_{4_w}) and the stoichiometric coefficients (n_{CH_4}') assuming a degradation efficiency of the organic carbon η<100% are identified in equations 18 and 19, respectively.

$$CH_{4_w} = C_{deg_{CH_4}} \cdot \frac{mol.wt.CH_4}{mol.wt.C} \left[\frac{g}{day}\right] \quad (18)$$

$$n_{CH_4}' = \frac{CH_{4_w}}{mol.wt.CH_4} \text{ [mol]} \quad (19)$$

Assuming the molar volume of a gas under standard conditions (v_{STP} [L/mol]), it is possible to predict the volume of methane obtained (CH_{4_v}) by the AD process and the corresponding biogas volume (v_{biogas}) (eqs. 20-21). In SC1, given the lower heating value of methane LHV [kWh/m^3_{STP}], and an electricity conversion efficiency η_{el}, it is possible to predict the amount of electricity produced by using the biogas entirely for electricity production (EL_{CH_4}), according to equation 22. If, on the other hand, the amount of biogas produced is used to produce biomethane (SC2), it is necessary to predict the carbon dioxide in the biogas (CO_{2_v}), as shown in equation 23.

$$CH_{4_v} = n_{CH_4} \cdot v_{STP} \left[\frac{m^3_{STP}}{day}\right] \tag{20}$$

$$v_{biogas} = \frac{CH_{4_v}}{\%CH_4} \left[\frac{m^3_{STP}}{day}\right] \tag{21}$$

$$EL_{CH_4} = CH_{4_v} \cdot LHV \cdot \eta_{el} \left[\frac{kWh}{day}\right] \tag{22}$$

$$CO_{2_v} = v_{biogas} \cdot \%CO_2 \left[\frac{m^3_{STP}}{day}\right] \tag{23}$$

Therefore, in SC2, the methane yield of the upgrading treatment ($v_{bio_{CH_4}}$) can be identified (eq. 24).

$$v_{bio_{CH_4}} = CH_{4_v} + \left(CO_{2_v} - CO_{2_v} \cdot \eta_{rem}\right) \left[\frac{m^3_{STP}}{day}\right] \tag{24}$$

Where η_{rem} is the carbon dioxide removal efficiency of the upgrading unit.

The daily electricity demand of the AD (EL_{AD} [kWh/day]) and the upgrading facilities (EL_{bio}[kWh/day]), depend on the unit energy consumption due to AD el_{AD} [kWh/day] and upgrading facilities el_{bio} [kWh/day] per the total mass of SS (eq. 25) and biogas volume (v_{biogas}) (eq. 26), respectively. In SC3, it is necessary to split the biogas volume produced in:

- biogas required to meet the energy demand of the AD plant ($v_{biogas_{EL-AD}}$).
- Biogas to be sent to the upgrading unit to produce biomethane (v''_{biogas}).

In this respect, the volume of methane needed to meet the energy demand from the AD plant ($CH_{4_{v,EL-AD}}$) was identified in equation 27).

$$EL_{AD} = el_{AD} \cdot m_{ss} \left[\frac{kWh}{day}\right] \tag{25}$$

$$EL_{bio} = el_{bio} \cdot v_{biogas} \left[\frac{kWh}{day}\right] \tag{26}$$

$$CH_{4_{v,EL-AD}} = \frac{EL_{AD}}{LHV \cdot \eta_{el}} \left[\frac{m^3_{STP}}{day}\right] \tag{27}$$

Assuming the $\%CH_4$ (already defined in eq. 14) it is possible to predict the volume of biogas required to meet the energy demand of the AD plant (eq. 18). Therefore, the theoretical volume of biogas to be sent to the upgrading unit (v'_{biogas}) is provided in equation 29:

$$v_{biogas_{EL-AD}} = \frac{CH_{4_{v,EL-AD}} \cdot 100}{\%CH_4} \left[\frac{m^3_{STP}}{day}\right] \tag{28}$$

$$v'_{biogas} = v_{biogas} - v_{biogas_{EL-AD}} \left[\frac{m^3_{STP}}{day}\right] \tag{29}$$

To identify the actual volume of biogas to be sent to the upgrading unit (v''_{biogas}) is firstly necessary to calculate the electricity consumption for the v'_{biogas} upgrading (EL'_{bio}) according to equation 30. Secondary, it is necessary to identify the methane volume required to produce the electricity consumption for the v'_{biogas} $\left(CH_{4_{v,EL-bio}}\right)$ and the corresponding volume of biogas, showed in equations 31 and 32, respectively.

$$EL'_{bio} = el_{bio} \cdot v'_{biogas} \left[\frac{kWh}{day}\right] \tag{30}$$

$$CH_{4_{v,EL-bio}} = \frac{EL'_{bio}}{LHV \cdot \eta_{el}} \left[\frac{m^3_{STP}}{day}\right] \tag{31}$$

$$v_{biogas_{EL-bio}} = \frac{CH_{4_{v,EL-bio}} \cdot 100}{\%CH_4} \left[\frac{m^3_{STP}}{day}\right] \tag{32}$$

Therefore, the actual amount of biogas volume sent to the upgrading unit is (eq. 33):

$$v''_{biogas} = v'_{biogas} - v_{biogas_{EL-bio}} \left[\frac{m^3_{STP}}{day}\right] \tag{33}$$

To identify the amount of biomethane produced to be sent to the upgrading unit ($v''_{bio_{CH_4}}$), it is necessary estimate the updated values of methane volume (CH_{4_v}'') and carbon dioxide (CO_{2_v}''), depending on v''_{biogas}, according to equations 34-36.

$$CH_{4_v}'' = v''_{biogas} \cdot \%CH_4 \left[\frac{m^3_{STP}}{day}\right] \tag{34}$$

$$CO_{2_v}'' = v''_{biogas} \cdot \%CO_2 \left[\frac{m^3_{STP}}{day}\right] \tag{35}$$

$$v''_{bio_{CH_4}} = CH_{4_v}'' + \left(CO_{2_v}'' - CO_{2_v}'' \cdot \eta_{rem}\right) \left[\frac{m^3_{STP}}{day}\right] \tag{36}$$

Moreover, it is necessary to consider the amount of electricity that could be obtained from CH_{4_v}'', to calculate the opportunity emissions (eq. 37):

$$EL_{CH_4}'' = CH_{4_v}'' \cdot LHV \cdot \eta_{el} \left[\frac{kWh}{day}\right] \tag{37}$$

The emissions corresponding to each of the three scenarios ($em_{SC1}, em_{SC2}, em_{SC3}$) considered depend on the emission factors from the national electricity grid (f_{grid_e} [$kgCO_{2_{eq}}$/kWh]) and from the gas grid ($f_{grid_{NG}}$ [$kgCO_{2_{eq}}/m^3_{STP}$]), according to equations 38-40.

$$em_{SC1} = \left(EL_{AD} - EL_{CH_4}\right) \cdot f_{grid_e} + v_{bio_{CH_4}} \cdot f_{grid_{NG}} \left[\frac{kgCO_{2_{eq}}}{day}\right] \tag{38}$$

$$em_{SC2} = \left(EL_{AD} + EL_{bio}\right) \cdot f_{grid_e} + \left(EL_{CH_4} - EL_{AD} - EL_{bio}\right) \cdot f_{grid_e} - v_{bio_{CH_4}} \cdot f_{grid_{NG}} \left[\frac{kgCO_{2_{eq}}}{day}\right] \tag{39}$$

$$em_{SC3} = -v''_{bio_{CH_4}} \cdot f_{grid_{NG}} + \left(v_{bio_{CH_4}} - v''_{bio_{CH_4}}\right) \cdot f_{grid_{NG}} + EL_{CH_4}'' \cdot f_{grid_e} \left[\frac{kgCO_{2_{eq}}}{day}\right] \tag{40}$$

The generated emissions have been assumed as positive contributions, while the avoided emissions have been assumed as negative contributions.

III. CASE STUDY

The developed model has been applied to the real full-case study referred to the SS produced in the WWTP "Bari Ovest", located in the metropolitan city of Bari. It is one of the largest plants in Southern Italy. It has been recently redesigned to increase treatment capacity from 240,000 Population Equivalent (PE) to 360,000 PE. In compliance with the national legislation, the SS treated in WWTP is stabilized by adopting AD. The biogas produced in the current plant configuration is sent to a cogeneration plant to produce electricity and heat. The physic-chemical characteristics of the SS treated are summarized in table 1.

TABLE I
PHYSIC-CHEMICAL CHARACTERISTICS OF THE SS ASSUMED FOR THE APPLICATION OF THE ANALYTICAL MODEL TO THE "BARI OVEST" PLANT

Variable	**Unit of measurement**	**Value**
m_{ss}	[g/day]	$75*10^6$ [26]
TS	[g/day]	$18*10^6$ [26]
VS	[g/day]	$12.96*10^6$ [26]
C%	[%wt. VS]	51 [27]
H%	[%wt. VS]	7.4 [28]
O%	[%wt. VS]	33 [28]
N%	[%wt. VS]	7.1 [28]
S%	[%wt. VS]	1.5 [28]
mol.wt. C	[g/mol]	12
mol.wt. H	[g/mol]	1
mol.wt. O	[g/mol]	16
mol.wt. N	[g/mol]	14
mol.wt. S	[g/mol]	32
mol.wt. CH_4	[g/mol]	16
η	[%]	52 [26]
v_{STP}	[L/mol]	22.4
η_{el}	[%]	38 [29]
LHV	[kWh/ m^3_{STP}]	10.69
η_{rem}	[%]	98 [30]
el_{AD}	[kWh/g]	0.000101 [30]
el_{bio}	[kWh/m^3_{STP}]	0.29 [30]
f_{grid_e}	[$kgCO_{2eq}$/kWh]	0.327 [31]
$f_{grid_{NG}}$	[$kgCO_{2eq}$/ m^3_{STP}]	1.98 [32]

IV. RESULTS AND DISCUSSIONS

The model was applied, and the results achieved for each scenario are shown below (tab.2)

TABLE II
RESULTS OBTAINED BY THE APPLICATION OF THE ANALYTICAL MODEL TO THE CASE STUDY

	SC1	**SC2**	**SC3**
$C_aH_bO_cN_dS_e$ [mol]	$C_{550800}H_{959040}O_{267300}N_{65726}S_{6075}$		
$\%CH_4$ [%]	70		
$\%CO_2$ [%]	18.45		
CH_{4_v} [m^3_{STP}/day]	4,491		
v_{biogas} [m^3_{STP}/day]	6,415.7		
EL_{CH_4} [kWh/day]	18,243.34	-	-
v_{bioCH_4}[kWh/day]	-	4,514.67	-
EL_{AD} [kWh/day]	7,575		-
EL_{bio} [kWh/day]	-	1,860.55	-
$CH_{4_{v,EL-AD}}$[m^3_{STP}/day]	-	-	1,864.75
$CH_{4_{v,EL-bio}}$[m^3_{STP}/day]	-	-	267.84
v''_{bioCH_4} [m^3_{STP}/day]	-	-	2,367.9
EL''_{CH_4} [kWh/day]	-	-	9580.3
em_{SC1} [$kgCO_{2_{eq}}$/day]	5,450.5	-	-
em_{SC2} [$kgCO_{2_{eq}}$/day]	-	-2,973.5	-
em_{SC3} [$kgCO_{2_{eq}}$/day]	-	-	2,694.96

The predicted composition of obtainable biogas includes 70% methane and around 18% carbon dioxide. The predicted v_{biogas} ensured by the plant is around 6,500 [m^3_{STP}/day]; this value is consistent with data available in industries practices [26]. Moreover, the electricity produced in SC1 exceeds the energy demand of the AD plant; therefore, the electricity surplus will be sent to the grid. The emissions corresponding to different scenarios are shown in figure 2. It is possible to observe that only in SC2 emissions are generated (3,085.42 $kgCO_{2eq}$/day). They depend on the supply of the AD plant and biogas upgrading unit from the national electricity grid. Nevertheless, SC2 is the scenario with the highest amount of avoided emissions (-8,939.05 $kgCO_{2eq}$/day). This effect depends on the emission factor of the gas grid $f_{grid_{NG}}$ (1.98 $kgCO_{2eq}/m^3_{STP}$); it is significantly higher than to emission factor of the national electricity grid f_{grid_e} (0.327 $kgCO_{2eq}$/kWh).

Consequently, the amount of avoided and opportunity emissions are strictly related to the amount of biomethane produced and sent into the grid. Consistent with this aspect, in the case of electricity production alone (SC1), the highest amount of opportunity emissions are identified. It results that, by comparing the avoided emissions of three scenarios, in SC2 are identified as the higher avoided emission than SC3 and SC1, respectively.

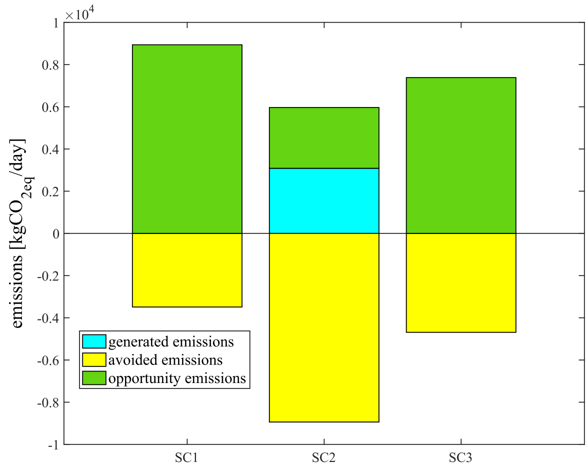

Fig 2. Predicted emissions in WWTP "Bari Ovest" for each scenario.

Therefore, SC2 is the best scenario from an environmental perspective; in this case, negative total emissions (-2,973.5 $kgCO_{2eq}$/day) were predicted (fig. 3). This means that the avoided emissions of SC2 are greater than generated and opportunity emissions.

The trend of the emission functions considered in the three scenarios ($em_{SC1}, em_{SC_2}, em_{SC_3}$) evaluated with respect to $f_{grid_{NG}}$ is shown in figure 4. Three break-even points $f_{grid_{NG}}$ were identified. In the case of $f_{grid_{NG}}$ is lower than 0.66 $kgCO_{2eq}/m^3_{STP}$, the best environmental choice consists of using the entire amount of biogas to produce electricity (SC1).

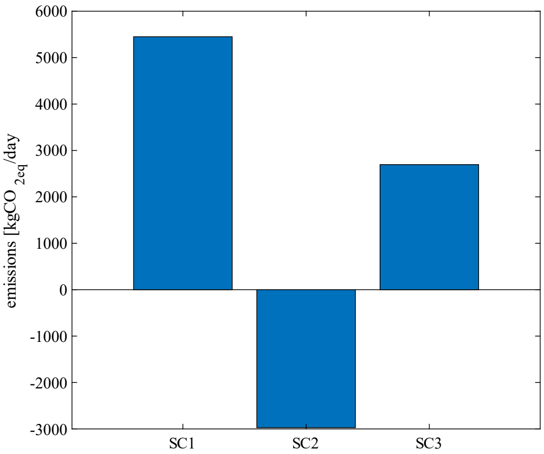

Fig 3. Predicted total emissions in WWTP "Bari Ovest" for each scenario.

The recovery options based on electricity and biomethane production (SC3), and only biomethane production (SC2), are less sustainable.

In the case of $\mathbf{f_{grid_{NG}}}$ is included between 0.66 and 1.05 $kgCO_{2eq}/m^3_{STP,}$ the best recovery option doesn’t change (i.e., SC1), but the SC2 become preferable to SC3 in environmental terms.

In the case of $\mathbf{f_{grid_{NG}}}$ is included between 1.05 and 1.39 $kgCO_{2eq}/m^3_{STP}$, the best environmental choice consists of producing only biomethane (SC2). The recovery options SC1 and SC3 are less sustainable.

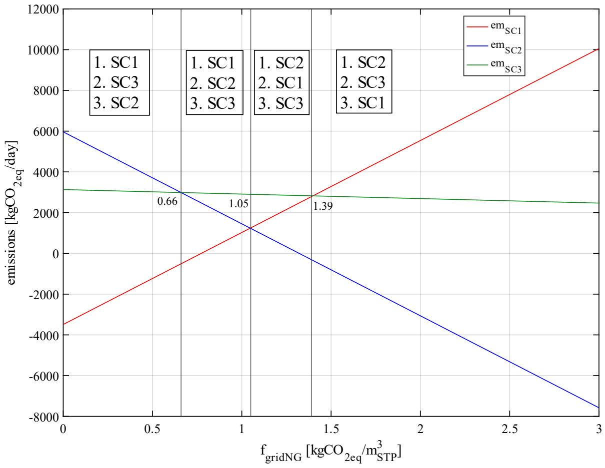

Fig 4. Trends of the emission functions by varying the emission factor from the gas grid for each scenario.

In the case of $\mathbf{f_{grid_{NG}}}$ is included between 0.66 and 1.05 $kgCO_{2eq}/m^3_{STP,}$ the best recovery option doesn’t change (i.e., SC1), but the SC2 become preferable to SC3 in environmental terms.

In the case of $\mathbf{f_{grid_{NG}}}$ is included between 1.05 and 1.39 $kgCO_{2eq}/m^3_{STP}$, the best environmental choice consists of producing only biomethane (SC2). The recovery options SC1 and SC3 are less sustainable.

In the case of $\mathbf{f_{grid_{NG}}}$ is higher than 1.39, the best recovery option doesn’t change (i.e., SC2), but the SC3 become preferable to SC1 in environmental terms. Therefore, under these assumptions, the recovery option of adopting the entire amount of biogas to produce biomethane and electricity is never preferable.

V. CONCLUSIONS

The objective of the present work was to develop an analytical model that, starting from the physic-chemical characteristics of the SS to be treated by an AD plant, predicts the composition of the obtainable biogas to identify the most sustainable recovery option in environmental terms. The model was applied to a real full-case study to identify three scenarios (i.e., SC1, SC2, SC3). The total emissions of three scenarios were compared. The results showed that the best alternative consists of producing only biomethane (SC2). It ensures a negative global amount of emissions (-2,973.5 $kgCO_{2eq}$/day). Moreover, it was observed that the emission factor from the gas grid ($f_{grid_{NG}}$) significantly affects the recovery option’s choice. In most cases, the recovery options based on electricity and biomethane are never sustainable.

The analytical model developed is consistent with the ongoing transition to a CE. First, it allows comparing three solutions for valorising a resource consistent with the CE transition. Second, the model allows quantifying the benefits or costs from an environmental point of view corresponding to each solution. Therefore, the decision-maker can identify a SS management solution consistent with the CE transition ensuring emissions minimization. Although the results are significant, this work shows limitations mainly related to the lack of direct emissions evaluations. Similarly, the energy needs of all WWTP facilities were not considered. To this concern, future studies could include these aspects and evaluate other plant solutions for biogas purification. Future developments should consider the influence of the process parameters of the AD and upgrading process on biogas and biomethane production. The assessment of the sustainability of a biogas recovery alternative cannot neglect the needed investment, the operating costs and revenues. On the one hand, biomethane production, using the biogas upgrading, requires higher investment and operating costs than other alternatives. On the other hand, it is reasonable that the revenues ensured from the sale of biomethane are higher than those generated from the sale of electricity due to different prices on the market. Therefore, future studies should address the economic aspect of the proposed alternatives not considered in the current study.

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