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A Framework for Biogas Exploitation in Italian Waste Water Treatment Plants

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Effective utilisation of biogas is an important step in increasing usage of renewable energy, due to the great flexibility that solar and wind power in particular lacks. Biogas generated through anaerobic digestion (AD) of sewage sludge addresses environmental concerns together with creating electricity generation potential. There is currently no optimisation-based decision-support framework to determine the best use of biogas from a Waste Water Treatment Plant (WWTP), and provide a market outlook for each of the options. This work proposes a novel multi-period Mixed Integer Linear Program (MILP) model for dispatch and selection of technologies capable of exploiting biogas produced from sludge. The novelty is also highlighted by extrapolating the optimised results to a broader analysis of 855 Italian WWTPs with Population Equivalent (P.E.) > 20,000. The use of real input data provides a unique added value to the work. The modelling framework is applied to several case studies. Results show that 7–23 % savings in operating costs are possible from integrating three systems to exploit biogas, and the trade-offs between capital and operating costs affect the optimal system choice. Furthermore, market driven scenarios are used to analyse how to improve the economic performance.

1. Introduction

Wastewater treatment is one of the most expensive public utilities accounting for more than 1% of Europe's electricity consumption (Enerwater, 2010), reduction of the energy use and emissions is essential to achieve the EU plan for a climate-neutral economy by 2050. Biogas produced from AD is converted using conventional devices such as Solid Oxide Fuel cells (SOFC) and Internal Combustion Engines (ICE) to heat and power, or upgraded to produce biomethane. Advanced biogas upgrading is needed to convert biogas into a storable fuel or for grid injection. Biogas, besides having the distinct advantage in controlling organic waste can produce carbon dioxide (for the food and beverage industry), fertilizer, and methane which is useful in various industrial applications (solvents, insecticide industry and plastic). Hence, there is need for an optimal framework to determine the best use of biogas for any site, since the decision is non-trivial. The high quality residual heat from energy conversion devices like the SOFC and ICE improves biogas production through thermal pre-treatment of the substrate for AD (Saadabadi et al., 2019).

Previous works on biogas exploitation focus on modelling the AD process (Anyaoku and Baroutian, 2018), biogas fed SOFC neglecting other exploitation paths (Saadabadi et al., 2019), techno-economic aspects of SOFC integration and financial appraisal of a biogas to electricity project (Govender et al., 2019), thermodynamic analysis of biogas fed SOFC (Prodromidis et al., 2017) and transient numerical modelling of waste to energy technologies (Montorsi et al., 2018). Some other authors focus on biomethane production (Paolini et al., 2018), detailed simulation of the biogas upgrading process (Vogtenhuber et al, 2018), and techno-economics of biomethane production (Aguilera and Ortiz, 2016). Few attempts have been made to compare biogas exploitation paths, and no work has considered extrapolating from the basis of a detailed optimisation framework to WWTPs in a country.

Gandiglio et al. (2016) compared three biogas exploitation paths from an energetic and economic point of view. However, the basis was a simulated energy system. Whilst simulations are useful, they do not capture trade-offs nor determine the dispatch of technologies taking into account biogas availability throughout the year, and energy prices. The cost of electricity and natural gas drive the selection of exploitation paths, and if not included

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in decision making, outputs from a simulation could be misleading often times resulting in lower revenues. A similar analysis is done in Wu et al. (2016) but focusing on electricity generation, again the basis is a simulation of the plant. Hakawati et al. (2017) also compared biogas-to-energy routes using final energy consumption/ energy efficiency based on simulation of the options. No study has been undertaken to quantify the market share of each exploitation path in a country building on detailed optimisation. This is required to determine how each technology fares in the market, since whilst a single technology maybe selected for a site, a mix is usually the case in a national scenario. The choice of technology, dispatch of systems and sizing the market for policy making is non-trivial. Therefore, a systematic framework is required.
The novel methodology developed in this work expands the optimisation model in Giarola et al. (2018) to include different exploitation paths (Figure 1a). The method is then applied to the WWTP archetypes identified by Sechi et al. (2018). Another novelty is the detailed economic analysis of different scenarios, for which the basis is the optimisation framework and extrapolating to all the WWTP in Italy with secondary treatment (data available from Water Base, 2014). The methodology presented in relevant for exploiting methane use in industry, biogas to fertilisation and CO_2, biogas reforming to produce hydrogen. This present work aims to provide an overview of biogas exploitation paths in an Italian context, focusing on WWTP with P.E. greater than 20,000. Such a method can aid policy makers in the decision process for biogas use.

2. Methodology

2.1 Energy system under consideration

A schematic of the energy system under consideration is in Figure 1a. The site currently uses a biogas boiler for heat demand (backed-up by a natural gas boiler), and electricity is imported from the grid. Integrating an SOFC or an ICE means some of the grid electricity and natural gas can be displaced. Upgrading biogas to biomethane, implies the site energy demand would need to be satisfied from a natural gas boiler and electricity imported; this is often neglected in studies on biogas upgrade. Each of the three exploitation paths is applied to the WWTP archetypes (Sechi et al., 2018) as shown in Figure 1b to ensure that extrapolation to an Italian context accounts for scale.

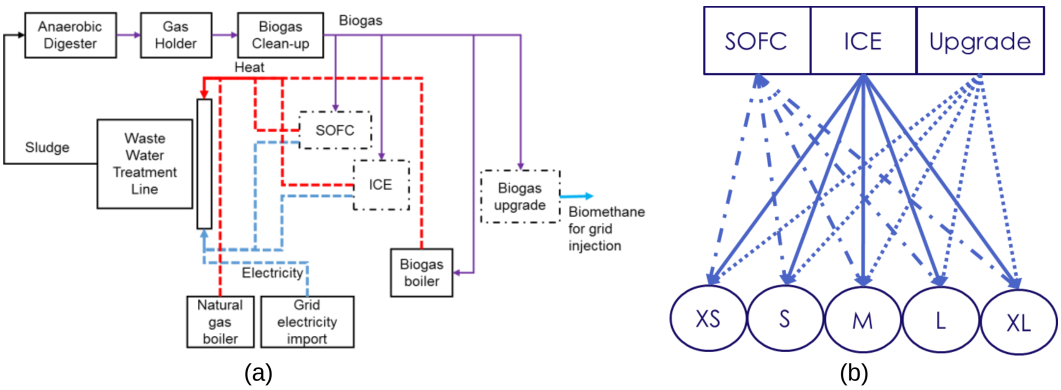

Figure 1: Energy system and WWTP archetypes (a) Energy system schematic and (b) Methodology overview

2.2 Mathematical optimisation framework

The optimisation framework is necessary to select the best technology and system to exploit biogas. Hence it is formulated as a multi-period MILP problem in GAMS. The optimisation forms the basis for the economic assessment, which in turn forms the basis for the Italian Market analysis. The objective in Eq(1) is formulated to minimise the Equivalent Annual Cost (EAC) defined as the sum of the Annualised Capital Cost (ACC), the fuel costs (FC) and maintenance costs (MC) and the cost associated with grid electricity import (CW^{Grid}).

$$Min: [ACC + FC + MC + CW^{GRID}] \quad (1)$$

The ACC is defined in Eq(2). Where Size is the technology size, Z is binary variable for technology selection, and IC is the installed capital, and *i* represents the set of all technologies.

$$ACC = AF \times \sum_i \left(\left(Size_i \times Z^i \right) + (IC_i) \right) \quad (2)$$

Constraints include the balance around biogas flow (B) in Eq(3), heat (Q) in Eq(4) and electricity (W) in Eq(5). The biogas can be kept in a holder. Where BGD and BGS are biogas wasted due to shut down and start-up events respectively, BOI is boiler, and *t* represents the time period. BBOI and NGBOI are biogas and NG boilers, PSD and PSU are power absorbed during shut down and start-up events.

$$\mathrm{GasHolder}_{t+1} - GasHolder_t + Bflare_t + BGD_t + BGS_t + B_t^{SOFC} + B_t^{ICE} + B_t^{Upgrade} + B_t^{BOI} = 0 \tag{3}$$

$$Q_t^{SOFC} + Q_t^{ICE} + Q_t^{BBOI} + Q_t^{NGBOI} - Q_t^{DEMAND} = 0 \qquad \forall\, \mathrm{t} \in \mathrm{T} \tag{4}$$

$$W_t^{SOFC} + W_t^{ICE} + W_t^{GRID} + PSD_t + PSU_t - W_t^{DEMAND} = 0 \qquad \forall\, \mathrm{t} \in \mathrm{T} \tag{5}$$

Ramping constraints, and biogas and electricity consumption for start-up and shut-down events are provided below: r_{up} is the ramp rate of the CHP technologies. Where Y is the binary variable for operation, and τ the maximum number of hours in any time period *t*.

$$W_t^i + W_{t-1}^i \leq r_{up}^i \times \tau \tag{6}$$

$$PSD_t^i \geq PSD_{abs}^i \times \tau \times Y_t^i \tag{7}$$

$$BGD_t^i \geq BGD_{abs}^i \times \tau \times Y_t^i \tag{8}$$

Eq(7) and Eq(8) can be replicated for power and biogas absorbed during start-up events. Eq(9) is formulated to choose the technology and determine the electricity produced. Eq(10) states that technology can be selected but may not operate in a time period.

$$W_t^i - size_i \times Y_t^i \leq 0 \tag{9}$$

$$Z^i - Y_t^i \geq 0 \tag{10}$$

The economic assessment measures the EAC, the operating costs, and the savings from selecting the technologies. This is calculated by subtracting the operating costs for the business as usual system from the selected system. An income can be generated by injecting biomethane into the grid. Extrapolating to the national context includes designing for each archetypes (Figure 1b) and accounting for the number of plants in each of the archetypes as shown in Table 1. The system with the lowest EAC dominates the market, and this is applied to the Italian context under different scenarios based on sensitivity to energy prices and capital cost. The five scenarios in addition to the Base scenario (with existing market conditions) are: (1) a higher electricity price, (2) a lower electricity price, (3) lower SOFC capital, (4) combination of (1) and (3), and (5) Biogas injection price. The computational time is 1.2 s using Cplex solver in GAMS on an Intel(R) core(TM) i7-6700 CPU.

3. Industrial case study

The case study under consideration is the WWTP sector in Italy. Two real sewage treatment plants with domain in the production of biogas forms the basis for the archetypes analysis in Sechi et al. (2018). There are 855 WWTP's in Italy with P.E. greater than 20,000 (Table 1). The biogas produced, heat and electricity demand for the plants are provided in Table 1. Costs assumptions for the SOFC and ICE are in Giarola et al. (2018). The CAPEX for the upgrade is 799 Euro/ kW, and its maintenance is 0.5 Eurocents/ kWh. The technology lifetime is 20 years, and a discount rate of 5 % is applied. The objective is to determine the best technology for biogas exploitation and measure it's penetration in the Italian Market under different scenarios.

Table 1: P.E., number of plants, biogas produced and energy demand in WWTPs

WWTP Archetype	Population Equivalent (P.E.)	Number of plants	Total biogas (GWh/y)	Total heat demand (GWh/y)	Total electricity demand (GWh/y)
XS	20,000-60,000	554	282	69	152
S	60,001-150,000	202	309	83	164
M	150,001-350,000	64	229	47	92
L	350,001-750,000	25	214	58	114
XL	750,000-1,100,000	10	209	55	109

4. Results and discussion of results

4.1 Energy system dispatch

The novel optimisation framework is able to determine the dispatch strategy for the technologies considered. The heat and electricity demand for the conventional system (Figure 2a) are met with a biogas boiler and grid electricity import. A NG boiler is used to provide back-up heating for all systems (Figure 2a – 2d). Integrating an SOFC reduces the grid electricity import (Figure 2b). Upgrading biogas to biomethane implies the heating demand needs to be satisfied by a NG boiler, and all electricity imported from the grid (Figure 2d). On average heat and electricity produced from the SOFC can satisfy 24-27.4 % of the energy demand.

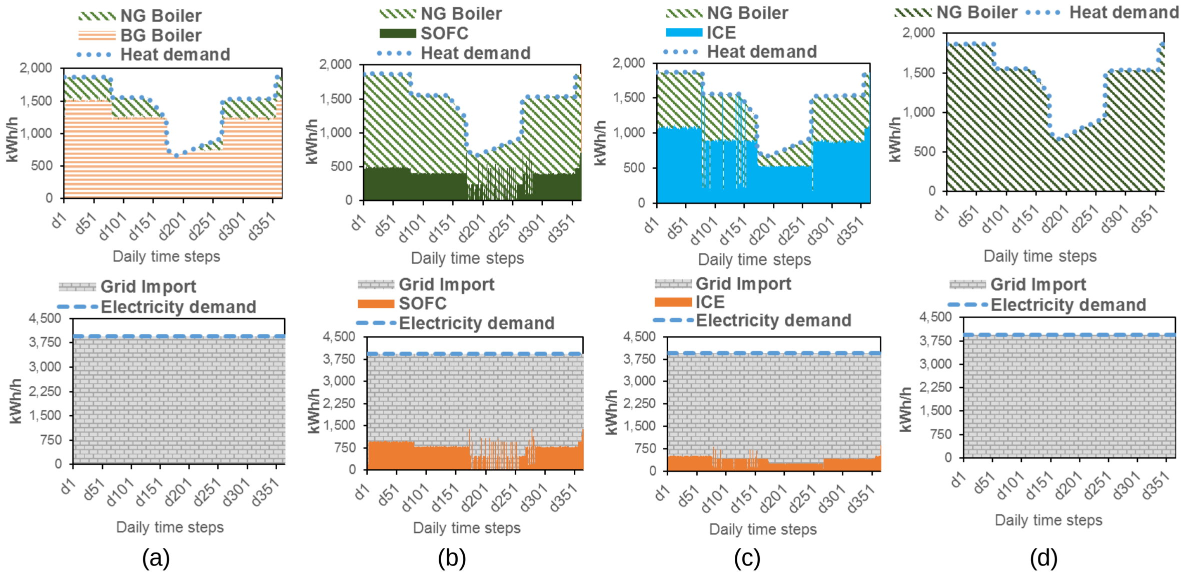

Figure 2: Operating schedule for (a) conventional system, (b) SOFC integration, (c) ICE integration and (d) biogas upgrade. Top four figures are the heating profiles and bottom four are the electricity profiles for an XS WWTP archetype.

4.2 Economic assessment

Upgrading biogas to biomethane has the lowest annualized capital investment for the XS (Table 2), and the highest operating costs (for all archetypes) since the energy demand needs to be met using heat from a NG boiler and grid electricity (Figure 2d). The SOFC has the lowest operating cost due to its higher electrical efficiency compared to the ICE, resulting in more grid electricity displacement. However, the SOFC high capital investment in the current term reduces its economic attractiveness. Without incentives for injection of biomethane to the grid income from upgrading biogas is zero. Scenario 5 considers biomethane injection tariff.

Table 2: System Economic Output

		XS	S	M	L	XL
Annualised Capital Investment (Euro/y)	SOFC	97,726	195,452	293,178	1,074,985	2,540,873
	ICE	17,682	36,547	57,726	201,265	476,656
	Upgrade	15,382	39,472	81,545	201,446	487,258
Operating costs (Euro/y)	SOFC	213,673	464,646	927,164	1,869,394	3,644,678
	ICE	224,986	485,818	960,326	2,050,207	3,914,193
	Upgrade	269,677	606,513	1,193,650	2,611,419	5,096,165
Savings/ income (Euro/y)	SOFC	27,826	57,515	143,559	430,508	690,932
	ICE	16,513	36,343	166,620	249,695	421,417

4.3 Sensitivity analysis

The scenarios definition is provided in the methodology section. For all WWTP archetypes, a combination of lower SOFC capital and higher electricity price gives the SOFC the lowest EAC (Figure 3). The EAC for biogas upgrade is lowest in scenario 5 (with biogas injection tariff) especially for the L and XL plants where the biomethane produced is highest (Figure 3). Exploiting biogas using the ICE (an established technology) is attractive due to its low capital investment. However, it is expected that the SOFC will be competitive from 2020.

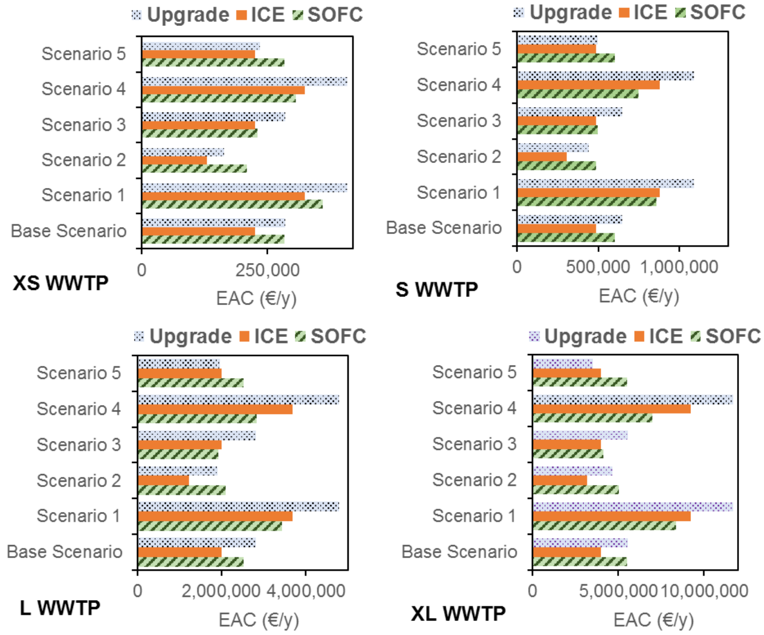

Figure 3: Economic assessment for all WWTP archetypes

4.4 Italian outlook

This paper builds on the optimized results for each WWTP archetype to provide an Italian market outlook for biogas exploitation. Such an analysis has never been done before. A technology will dominate the market if its EAC is the lowest. Based on this, the ICE dominates the market in most scenarios except for a future SOFC target CAPEX and a higher electricity price i.e. Scenario 4 in Figure 4. The SOFC occupies 28% of the market in scenario 1. With biogas injection price, the upgrade occupies the L and XL WWTP archetypes market and occupies 4.1% of the market overall (Figure 4). Market outlook analysis is necessary to inform policy and manufacturers on conditions required to increase biogas use in WWTP. Conversion of biogas to biomethane is already a strategic target in many countries, hence more incentives may become available.

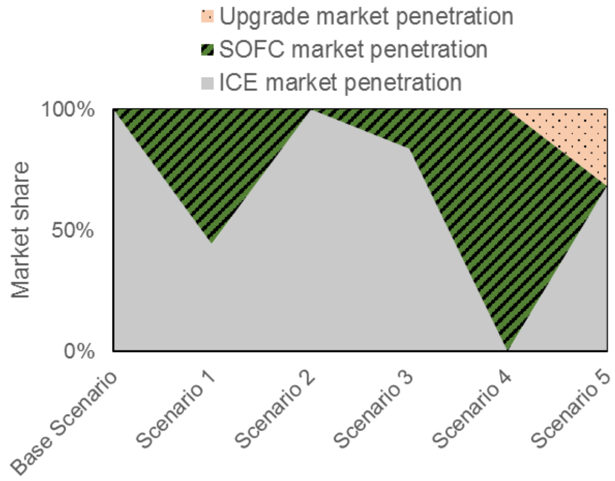

Figure 4: Italian market size using all 855 WWTP with P.E. > 20,000

5. Conclusions

Biogas exploitation reduces the need for carbon laden energy sources like NG and grid electricity in WWTPs. Most importantly by producing biogas from sludge, more value is added to liquid waste. The challenge is deciding the right combination of technology and systems to exploit the biogas. This work presented a novel optimisation-based decision-support framework, which is also capable of providing a country outlook on biogas exploitation. Results from the detailed economic assessment show that the highest operating costs and lowest capital are associated with the upgrade option especially for an XS archetype, and the lowest operating cost and highest capital associated with the SOFC (for all WWTP archetypes). Such trade-offs make the choice of the best use of biogas non-trivial justifying the need to build comparisons on an optimisation basis. An analysis considering the Italian WWTP sector shows that the ICE dominates using existing energy prices; however, the SOFC share increases to 2.9% for a lower electricity price, 27.7% for a higher electricity price, and 100% for a lower capital and higher electricity price. Upgrade occupies all the market from a P.E. greater than 750,000, when the incentive for biogas is included. The quantified market share is relevant for assessing cost reduction based on manufacturing volumes. Future work will include more options for biogas exploitation and expand the analysis to all WWTP in Europe. The financial viability of biogas projects can be improved if policy frameworks are amended to increase the market share of exploitation paths as part of the renewable programme.

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