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Micro-cogeneration based on solid oxide fuel cells: Market opportunities in the agriculture/livestock sector

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HIGHLIGHTS

- The livestock sector embeds a high and unexploited biogas energy potential.
- The majority of livestock farms requires small and micro-scale cogeneration systems.
- Solid Oxide Fuel Cells (SOFC) improve the energy performances of micro biogas plants.
- The economic assessment for SOFC in small livestock farms is presented.
- SOFCs can contribute to raising the share of bio-waste used for electricity.

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ABSTRACT

Bio-waste embeds an extraordinary renewable potential, and it becomes a source of energy savings when transformed into a valuable resource, like biogas. Cogeneration (CHP) from biogas employing high-temperature Solid Oxide Fuel Cells (SOFCs) scores a high sustainability level, thanks to improved environmental and energy performances. The synergy between the niche market of small/micro biogas producers and SOFCs might act as a springboard to open market opportunities for both SOFC commercialization and business upgrade of small farms. However, local regulations, waste management, renewable energy subsidies and, above all, availability of eligible sites, determine real chances for on-the-ground implementation.

Through a detailed analysis of the application scenario, this research aims at investigating opportunities for the experimentation of SOFC–CHP in small biogas plants and identifying the possible bottlenecks for future deployment. When it becomes relevant, energy conversion of livestock (especially cattle and swine) and agriculture waste requires SOFC modules from 10 kW_e to 35 kW_e. This is in line with the current status of SOFC suppliers. Moreover, considering the fuel cell market roll-out, the average levelized cost of electricity is expected to decrease from 0.387 €/kWh to 0.115 €/kWh, when electricity is produced from livestock waste available on-site.

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Introduction

The penetration of renewable power sources in the international energy mix is increasing significantly to reach global sustainability targets. Beside variable renewables (in the first instance, as solar and wind) which are not predictable, other renewables may play an important role in the upcoming years. In particular, pointing at the realization of circular energy chains, waste embeds an extraordinary energy potential and, thereby, it is already a form of storage. Consequently, waste may be converted into energy when it is needed, achieving a double benefit: on the one hand, energy production with a very cheap raw material and, on the other hand, reduction of the environmental burden due to disposal processes. Not all kinds of waste are suitable for this scope. However, large amounts of waste from the industry, urban areas and agricultural/livestock sector are adequate to be turned into a methane-rich fuel called, generally referred to as *biogas*. At the European level, in 2015, biogas share among all renewable energy sources (RES) for electricity generation[1] reached 12% out of a total of nearly 63 TWh. According to the *International Energy Agency* (IEA) statistics [1], electrical energy generation from waste-derived biogas features a sharp growing trend in the last 20 years. In particular, IEA classifies biogas sources in three families, namely municipal Solid waste (MSW), industrial waste and bio-waste (generally originated from agriculture and farming). The latter category appears to be the most promising, both in terms of absolute value and incremental trend. As Fig. 1-left shows, today the European electricity generation from biowaste-derived biogas is more than 60-fold the electricity potential registered in 1990, overcoming the energy potential embedded in municipal and industrial waste. Likewise, the share of bio-waste derived biogas into the Italian energy mix [2] for electricity generation has recently grown considerably (Fig. 1 -right). In 1990 bio-waste derived biogas was an unexploited resource.

Then, according to IEA stats referred to 2016, 8.3 TWh electricity were generated annually (Fig. 1-right), achieving a share of 14% in the overall electricity production from renewables.[1] On the other hand, biogas has been extensively used for heating application and, compared to the other RES used for the purpose, its share equals 44% (2.4 TWh).[2] Nonetheless, the energy potential coming for farms is still far to be fully exploited [3]. As GSE[3] reports, few biogas plants in Italy are below 50 kW_e. In details, plants with an installed power lower than 30 kW_e are about 10 (only for one it is declared that biogas is used in a CHP unit based on Internal Combustion Engine (ICE)) [4]. Moreover, as in many European countries, micro e small biogas plants receive higher subsidies [5], GSE's new tariff for renewable generators (GRIN [6]) set electricity generation from biogas on the higher tariff segment.

[1] As RES for electricity, beyond biogas, MSW/industrial waste, solar PV, wind and geothermal are considered.

[2] Beside biogas, MSW/industrial waste, geothermal and thermal solar are considered for heating applications.

[3] GSE (Gestore dei Servizi Energetici) is the Italian association in charge of energy management at national level, under the responsibility of the Ministry of Economics.

Energy conversion of biogas

Bio-waste is commonly converted into biogas through a biochemical process called anaerobic digestion. The technology is simple and well-known worldwide. Further, the most common utilizations for biogas are combined heat and power generation (CHP), heating (boilers) and − as recent trends on large plants show − upgrading to biomethane for injection into the gas grid. While bio-methane production is very promising yet feasible only on large scale biogas facilities, CHP seems to be the most cost-effective solution below 9 MW installed power. Approximatively, below this plant size, biogas upgrading to biomethane is far from being claimed feasible [3]. Upgrading is a cost-intensive process, since the connection to the gas grid requires high purification and pressure standards in line with local regulation. Moreover, it is not always possible for the production sites location with respect to gas grid infrastructure.

Looking at existing CHP plants, the average size expressed as the net electric power production is around 1 MW_e (for instance, ICEs by Jenbacher and Caterpillar [7]). However, public opinion regarding large-scale biogas facilities is often adverse to the success of this technology, for a matter of smell/landscape impacts and combustion-related emissions [8]. Moreover, besides the biogas potential exploited at present, most resources are allocated in small sites, which lack of great economies of scale [9]. Then, considering the waste-to-energy value chain, the overall sustainability is significantly jeopardized whether diffused waste amounts have to be collected and moved to a unique big biogas production facility. All these factors regarding logistic and sustainability of waste processing lead to define the ideal scenario to achieve waste-to-biogas conversion in small facilities. In particular, energy-conversion appears sustainable exactly where waste is produced.

Opening market opportunities to micro-scale biogas plants may be an answer to this issue. On one side, this means downscaling the anaerobic digestion section down to sizes that are suitable to process a small amount of bio-waste. Generally, micro-scale biogas plants are on-farm installations using only their own bio-waste resources and micro-scale biodigester appears to be simplified and downscaled versions of conventional biogas plants. On the other side, the new scenario calls for efficient micro-CHP systems, that can be easily integrated with a useful internal utilization of co-generated heat.

Beyond the fact of energy potential allocation, small waste-to-energy chains are featured by a higher level of sustainability, coping with the needs to dispose of waste locally without adding extra burdens on energy consumption and associated emissions (mostly caused by transportation). Whilst there are several reasons in favour, micro-scale facilities for biogas production and conversion are not widespread at present. Recent European projects[4] have already attempted at evaluating the market perspective of micro-digestion. These projects pointed out some issues concerning this poorly exploited market segment:

[4] References: BioEnergyFarm1 and BioEnergyFarm2.

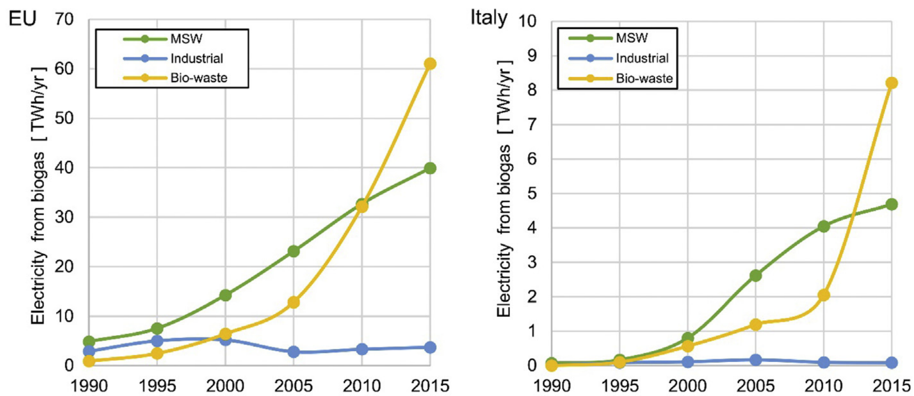

Fig. 1 – Electricity from biogas: EU data (left), Italy data (right) – Source IEA stats [1].

- Regulation-oriented technological development: different subsidy schemes among EU countries have led to significant divergences in the biogas sector development over the last decade. The occurrence of a favourable framework for a sufficiently long period fostered the creation and the success of several experiences, both on the bio-digester and CHP sides. This happened, for instance, in Germany. Moreover, in many countries, local regulations set limits on the electrical production capacity and the livestock production involved, conditioning the type of plant achieving full cost-effectiveness.
- Lack of a standardized definition of micro-digestion: no official statistics exist for this new market, and each European country has its own definition of "micro-digestion" in terms of plant capacity (see Table 1). The causes are basically two: local regulation into force and local technology suppliers. This point is well debated in the next subsection Micro-CHP based on Solid Oxide Fuel Cells: a state-of-the-art. The definition of micro digestion (and micro-CHP, accordingly) varies much in Europe, according to local policies which have fostered the development of the technology. From data displayed in Table 1, it appears that micro-scale biogas plants range from ~100 to 200 kW_e electric capacity (Italy, France, Austria) down to 10–50 kW_e (Belgium and, more extensively, Germany). This last example includes facilities below the conventional threshold set for biogas plant feasibility (50 kW_e [3,10]). Moreover, the choice of the organic substrate (bio-waste as liquid/solid animal slurry and manure with a total solid fraction between 4% and 30%) to produce biogas varies among the countries. The main difference, however, is due to the co-digestion of livestock waste and high share of food-processing/intermediate crops/silage. This practice is widely common as the biogas size grows, as it happens in France and Italy (up to 200–250 kW_e).

As a consequence, micro-digestion feasibility in most of European countries needs for revisions of the regulation.

Micro-CHP based on Solid Oxide Fuel Cells: a state-of-the-art

The market segment identified in the previous section shows high potentialities for CHP units based on Solid Oxide Fuel Cells (SOFCs). SOFCs manufactures supply products in the power range of 1–300 kW_e (refs: SolidPower, Convion, Bloomenergy, RedoxPower [11]). In this number, a few suppliers explicitly declare in the product data sheet that their SOFC systems can operate both on natural gas and biogas, provided that harmful compounds are removed from fuel gas used. The majority of commercial SOFC micro-CHP systems is designed to operate at a temperature of about 700–750 °C, since this is the optimal condition for the electrocatalytic performance of current SOFC materials (conversely, Low-Temperature SOFCs have been proved to be less effective for the occurrence of undesired reactions paths [12]). Then, most of commercial systems feature a fuel external pre-processing architecture. This means that methane contained in natural gas (alternatively, in biogas) is decomposed into a hydrogen-rich syngas upstream the SOFC. This process occurs by either steam/autothermal reforming or partial oxidation (POX) out of the SOFC stack [13]. Considering hydrogen yield as performance parameter, steam reforming is the best option as methane is not oxidized in the reformer, while POX and autothermal reforming consume part of the methane because of direct oxidation. As a consequence, this affects the energy efficiency of the system as a whole. For the sake of example, the stack efficiency drops from 60% in steam reforming to 52% in POX [14] (same SOFC stack operated at 800 °C and atmospheric pressure).

However, micro-CHP SOFC systems may increase their cost-effectiveness by decreasing the rate of external fuel pre-processing [15]. When this falls to zero, the entire amount of methane contained in the fuel cell feed is processed inside the SOFC [16]. Concerning that, many researchers have been working on this concept in the recent years. Moreover, in order to achieve good performances throughout the entire system lifetime, many suggest to premix natural gas/biogas with oxygen carrier gases upstream the fuel cell stack. This ends in two positive effects: on the one hand, it enables temperature uniformity over the cell surface [17] and on the other hand, it prevents unfavourable chemical reactions to occur. Alternatively, SOFC stack may be built on innovative materials which are more fit to operate on internal reforming mode [18–20]. Despite this is a breakthrough perspective, this is not a market-ready solution for the wide implementation of SOFC micro-CHP systems in the near future.

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Table 1 – Micro-scale biogas plants in EU countries, according to national definitions and local market status. The electric power range 50–250 kWe is assumed equivalent to a livestock waste throughput of 2500–12,500 tons/year. Data Source [3].

Country	Biowaste	CHP Capacity range (kW_e)
Austria	Slurry and solid manure	<100 (30–75)
Belgium	Liquid cattle manure	10–200
France	Dry manure and little straw, grass, intermediate crops, food-processing waste (TS 20–30%)	<100 (50–200)
	Liquid manure from farms (TS 6–14%)	
	Liquid manure from farms + other processing organic liquids (TS 4–10%)	
Germany	Liquid/solid manure and partly stackable biomass	<75 (30–75)
	Liquid manure + low shares of energy crops	<75 (7–75)
	Liquid or pre-digested substrates	<75 (10–75)
	Solid manure and stackable biomass with >30% TS	<75 (10–75)
Italy	Manure and silage	150–300

However, looking at the practical implementation of the SOFC systems ready for the market uptake, the commercial state of the art is considered for the analysis presented hereinafter. Therefore, all data regarding the technology readiness of the SOFC technology (included market prices evolution and material durability) are retrieved from EU reports focussing on 5–50 kW_e CHP units [21].

Technological advancements for micro-digestion plants

The micro-digestion market segment shows high potentialities for CHP units based on Solid Oxide Fuel Cells (SOFCs):

- From the technological point of view, high electric efficiency is scored even in facilities with a low installed power, where conventional systems exhibit a marked performance drop. Using biogas as a fuel, while ICE efficiency falls below 30% for installed power less than 50 kW_e, SOFC electric performance keeps stable around 50%;
- Looking at environmental repercussions, neither particulate matter nor NOx gaseous emissions occur in SOFCs exhaust streams. Moreover, SO_x emissions are avoided because the fuel gas needs a pre-treatment before being fed to the SOFC and assuring safe operation thereby [22];
- The utilization of a RES-based fuel is sound to improve the environmental performances from a life-cycle assessment (LCA) perspective too [23,24].

From a market analysis perspective, compared to ICE-CHP, SOFC can fill up this market segment specifically for installed power below 50 kW_e [11]. While the advantages of implementing SOFCs in biogas facilities are many, the main pitfall is represented by costs and reliability, as it is a nascent technology. A reduction in the system complexity is expected to have a favourable effect on the capital costs of the system, leveraging the impact of the SOFC technology, especially on small-scales.

Scope and outline

The current paper aims at evaluating the biogas potential embedded in small farms and, thereby, to assess the synergies between this unexploited share of bio-waste and the new market of micro-scale CHP based on SOFCs. From Table 1, it emerges that, in most cases, micro-scale biogas plants operate on liquid manure and, just partly, on energy crops waste (silage). For this evidence related to the European framework and for the general trends depicted in Fig. 1 plots, the market analysis presented in this paper regards specifically livestock farms. Hence, the market model is applied to an Italian case (Umbria region) to identify local targets for further experimentations in the framework of the research project *Tezio*. Moreover, some general features of ideal market conditions are pointed out, aiming at extending the results of this research at international level (at least considering EU countries which have an economical fabric similar to the Italian one). Hence, considering a state-of-the-art micro-CHP SOFC system architecture, a techno-economic study based on current economic data is presented, as well as future projections regarding the positive influences on SOFCs' components market prices caused by a wide use of SOFCs.

After depicting the framework of the research in this introductory section and pointing out the specific scope of the paper, the following sections address: the methodology implemented to perform the analysis (Section Methods), the results presentation (Section Results) and comprehensive discussion (Section Discussion) and a summary to conclude (Section Conclusion).

Methods

The methodology used in this paper features the following steps: first, data from the market potential users are acquired (subsection A local perspective of micro-scale biogas market: the case of Umbria), then the potential energy performance and economic indicators are calculated, according to the procedures described in subsections Energy performance and Economic assessment respectively.

A local perspective of micro-scale biogas market: the case of Umbria

Umbria is a small region in central Italy with a population of nearly 890,000 inhabitants (census 2019) over about 60 million Italian citizens. Cattle and swine farming are practised in the region, yet in rather small farms. This recalls the situation occurring in many other European countries [25]. Therefore, the following analysis may be replicated in a larger market.

Table 2 – Biogas yield from different substrates [3,8].

	Swine Manure		Cattle Manure		Corn Insulate
	Average	Range	average	Range	average
Total Solids (TS) $\%_{mass}$	4.4%	2.6–6%	8.2%	5.7–10.7%	31%
Volatile Solids (VS) $\%_{TS}$	70%	63–77%	73%	64–82%	
Biogas yield Nm^3/kg_{VS}	0.50	0.45–0.55	0.38	0.30–0.45	0.60
Methane fraction $\%_{vol}$	62.5%	60–65%	57.5%	55–60%	53%

Data concerning the number of cattle/swine farms in Umbria and their size distribution are retrieved from *Banca Dati Nazionale - Anagrafe Zootecnica* (BDN) [26,27]. The total number of cattle/swine heads (hd) comes from the annual census published by Istituto Nazionale di Statistica (*ISTAT*) [28]. All data used for this study are updated to years 2013–2017, in agreement with the latest version of public reports released by qualified agencies.

Energy performance

The energy conversion process consists of two subsequent steps: first, livestock waste conversion to biogas (anaerobic digestion) and second, biogas conversion to electricity (SOFC). The latter process requires a deep clean-up from impurities.

From waste to biogas

The energy potential of a biogas production site can be calculated considering: i) the animal breed type (manure productivity per animal head), ii) data about the anaerobic methanation of livestock waste (methane yield from a unitary amount of typical substrates). Common values regarding these parameters are displayed in Table 2. In addition, the following assumptions are set to size the energy system based on the conversion of animal waste:

- Dairy cattle manure daily production: from 40 to 50 kg/day/hd
- Beef cattle manure daily production: from 25 to 35 kg/day/hd
- Swine manure daily production: from 4 to 5 kg/day/hd.

This allows evaluating the equivalent power in terms of raw gas potential/net electricity production per each farm class.

Fig. 2 shows the equivalent power as raw biogas potential with regard to three categories of farms: beef and dairy cattle, as well as swine. The equivalent power varies in terms of quality and quantity, in agreement with animal breed metabolisms, age and weight, the quality of the substrate and the yield of the methanation process occurring in the waste digester. The variability ranges of the most significant parameters are resumed in Table 2.

The estimation of the equivalent power based on average values of total solids (TS), volatile solids (VS), methane yield and methane fraction appears a rational choice, bringing about results that are closer to the lower bounds. Therefore, this is a conservative hypothesis. Eventually, the possibility to run the plant in co-digestion is considered (manure + insilate). Table 2 also displays data about corn insilate, assumed as a conventional crop used for this process in Italian biogas facilities.

Livestock biogas features a high sulphur load, mostly in the form of hydrogen sulphide (H_2S). H_2S concentration may vary from 1000 to 8000 ppm_v [30,31] according to the feedstock. For cattle and swine manure, it is reasonable to assume 3000 ppm_v and 4000 ppm_v respectively (these numbers slightly overestimate measured H_2S concentration both in cattle and swine manure [32]). This fact calls for a deep clean-up from sulphur, in order to meet SOFC requirements (tolerance threshold to H_2S c.a. 1 ppm) [33]. This can be achieved by already available technologies, as further on described.

From biogas to electricity

For the purpose of this study, a basic SOFC micro-CHP system configuration is considered, in agreement with commercially available products [11]. These are usually designed to operate on grid natural gas (NG), so they are equipped with a sulphur filter suitable for NG S-based odorants loads and an external reformer where NG is decomposed into syngas (H_2 and CO) upstream the SOFC stack. Commercial systems with the external reformer have been proved fine also with biogas, achieving an electric efficiency of 50%–53% [34]. Such efficiency is declared by SOFC manufacturers, and it can be assumed true at the beginning of the SOFC stack lifetime. Then, SOFC performance faces a reduction due to degradation phenomena caused by the operation [35]: high temperature, exposure to carbon and trace pollutants, severe overpotentials. In commercial systems equipped with the external reformer, degradation rate measured over many hours of operation is lower than $1\%_{1000h}$ [11]. The degradation rate may vary according to the biogas reformate quality, thereby affecting the overall system energy performances. Besides the performance losses, this calls for a periodical substitution of the stack and related expenses. Technical reports state that, on average, the lifetime of ICEs running on biogas is around 70,000 h [10]. Therefore, based on current knowledge, it can be deduced that the lifetime of a SOFC stack[5] is much lower compared to ICE (40,000 vs 70,000 h). Nevertheless, considering a timeframe shorter than 40,000 h and a degradation rate of $1\%_{1000h,}$ the SOFC efficiency keeps higher than ICE's. As degradation rate reaches $2\%_{1000h}$ [15], SOFC performances begin to drop below ICE's.

Therefore, it is clear that the SOFC stack degradation rate is crucial information for a detailed feasibility study of micro-scale biogas CHP plants based on the SOFC technology. For

[5] The SOFC system lifetime is about 15 years, yet the core component – namely the stack – needs for frequent replacements [44].

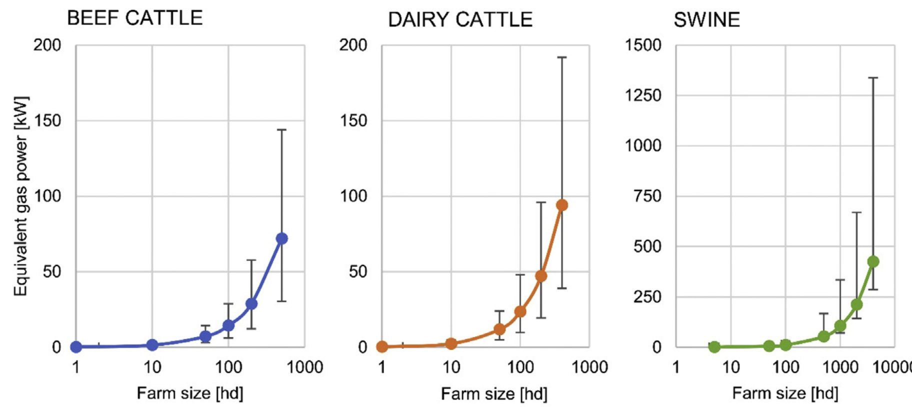

Fig. 2 – Equivalent power (based on raw biogas production) for each farm class: beef cattle (left), dairy cattle (centre), swine (right).

the sake of a preliminary market analysis, SOFC stack durability is accounted for considering the number of stack replacements needed in the lifespan of the micro-CHP system as a whole [21].

Economic assessment

In order to get an economic evaluation of the system proposed, this section presents the comprehensive methodology for the economic performance indicators calculations, as well as the basic assumptions to evaluate the cost of the main sections of the energy plant.

Economic analysis: indicators

In order to get an economic evaluation of the system proposed, the cost parameters here introduced are:

- the Total Cost of Ownership (TCO, Eq. (1)) of the plant, that is to say, the net present value of all cost items occurring during the lifetime[6] of a given system asset.

$$TCO = I_0 + \sum_{i=1}^{n} \frac{O\&M_i + R_i + F_i}{(1+r)^i} \tag{1}$$

- The Levelized Cost of Electricity (LCOE), representing the net present value of the unitary-cost of electricity generation, obtained during the lifetime of a given system asset. LCOE is a measure of costs which attempts to compare different technologies for electricity generation [36], and it corresponds to the minimum cost at which electricity should be sold to break-even the total cost over the lifetime of the project. IEA provides an analytical definition of LCOE [37], as in Eq. (2).

$$LCOE = \frac{I_0 + \sum_{i=1}^{n} \frac{C_{sys,i}}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+r)^i}} = \frac{I_0 + \sum_{i=1}^{n} \frac{O\&M_i + R_i + F_i}{(1+r)^i}}{\sum_{i=1}^{n} \frac{E_i}{(1+r)^i}} \tag{2}$$

In Eq. (1) and Eq. (2), the Net Present Value (NPV) of the sum of annual costs (subscript *i*) arising during the lifetime of the project (*n* - years) is considered. All costs are discounted with a rate *r*, which is assumed constant throughout the project. In addition to the investment occurring at the beginning of the project (I_0), the other system annual costs include operation and maintenance (*O&M*), components replacement (R) and operative expenditures (F). When biogas micro-CHP is concerned, I_0, O&M, R and F are referred to the acquisition, installation and operation of the three main parts of the plant, namely the anaerobic digester, the external biogas clean-up unit and the SOFC CHP unit. Finally, in Eq. (2), also the sum of actualized annual electric energy flows (E_i) is represented.

Economic analysis: unitary cost library and general assumptions

The system costs are analysed, considering the following breakdown:

- Anaerobic digestion: buildings (3210 € h/m^3, lifetime 20 years), machinery (2957 € h/m^3, lifetime 10 years, management expenses (202 € h/m^3 per year), maintenance (202 € h/m^3 per year) [10]; reference specific cost are expressed with regard to the unit biogas flow rate;
- Desulphurization: iron-sponge adsorption is chosen as a state-of-the-art method for a deep biogas clean-up, suitable to reduce the high H_2S load down to the level accepted at the SOFC inlet. Costs data are retrieved from Refs. [38], and results are: 9.66 €/year/LCE to abate 3000 ppm$_v$ and 12.88 €/year/LCE to abate 4000 ppm$_v$;
- SOFC CHP: installation costs, capital costs, maintenance and replacement costs and frequency, as reported in detail in Ref. [21]. Moreover, for this part, an analysis regarding the fuel cell market evolution is made starting from today's scenario and implementing a cost reduction forecast in the perspective of fuel cell production standardisation and further industrialization. Unitary costs fitting curve are

[6] As it is an economic evaluation, the concept of system lifetime is often referred to the depreciation time.

[7] LCE stands for Lactating Cow equivalent. This is an equivalence term to compare different breed farming in terms of biogas productivity. 1 Beef cow = 0.6 LCE, 1 Dairy cow = 1 LCE, 1 Hog = 0.06 LCE.

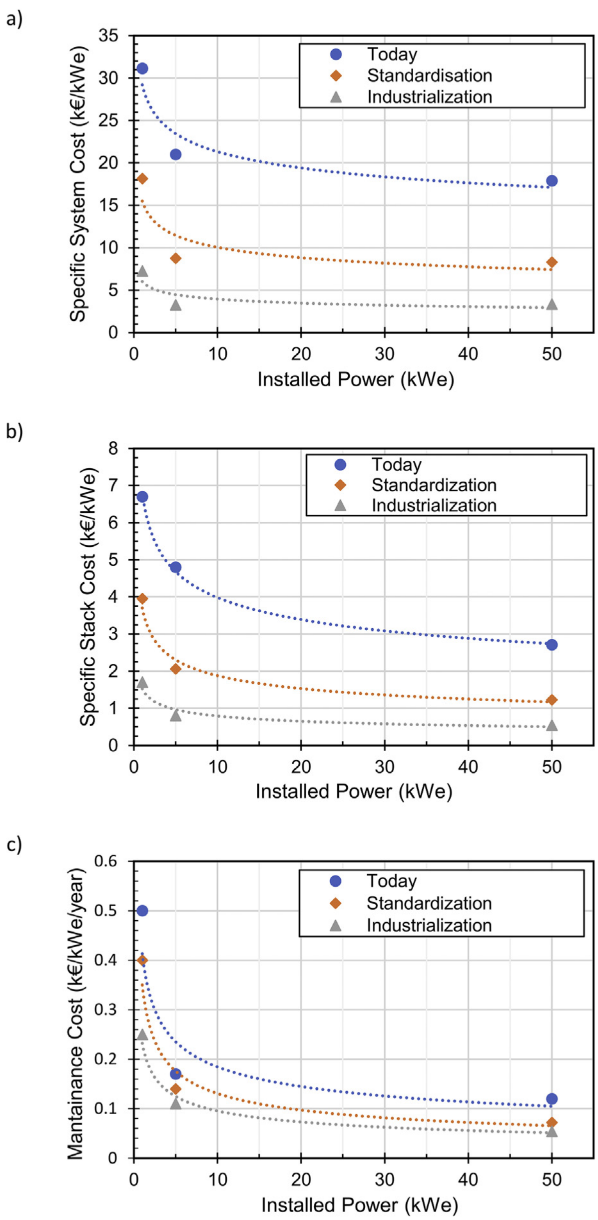

Fig. 3 – SOFC unitary costs evolution power-law fitting curves in three market scenarios: today, standardized manufacture and industrial manufacture. Data are retrieved from Ref. [21,39]. a) Specific system costs: this includes the initial investment costs for the stack, BoP components, as well as other installation costs; b) Specific stack costs: this is the replacement cost for the SOFC stack, occurring periodically because of the SOFC material degradation (it is assumed every 5, 6 and 7 years for the "Today", "Standardisation" and "Industrialization" respectively; c) Yearly specific maintenance cost.

reported in Fig. 3. Conversely, since anaerobic digester and desulphurization unit components are state-of-the-art, the same study does not appear with their regard.

In addition to that, common assumptions to carry out the economic evaluation are:

- Overall duration of the project: 20 years;
- Hours of operation per year: 8400 h/year;
- Discount rate r = 8%;
- For the calculation of LCOE, the SOFC micro-CHP generator energy production is referred to constant nameplate power operation (Table 6) for 8400 h/year;
- SOFC degradation is considered in terms of stack periodical substitution (Fig. 3-b);
- Zero costs are supposed with regard to livestock waste supply, since it is assumed that the micro-digestion plant operates on livestock waste available on-site;
- No subsidies are assumed in this study, in order to provide a general overview which does not depend on specific national/regional policies. This is a conservative assumption, and thus in the event of subsidiary policies, economic indicators would be more favourable than the ones shown in this report.

Results

This section presents the main outcomes of the research: first, the market of possible users is quantified (subsection Market context assessment), then relevant case-studies are highlighted (subsection Relevant case-studies), so that the energo-economic assessment is detailed (subsection Energo-economics of SOFC in the agricultural/livestock market).

Market context assessment

In Umbria, regional farms account for about 2% of the total farms held on the national ground [28]. Most of farms registered by BDN are classified as domestic (nearly 70% for cattle and 95% for swine) and small (25% and 3% for cattle and swine respectively). The details in terms of livestock farms and total livestock heads are shown in Table 3. However, while there are many farms of such tiny size, the total number of heads is significantly distributed in medium and large size farms. The cumulated distributions are shown in Fig. 4 separately for cattle and swine farms.

Looking at micro-scale biogas plants, the energy potential embedded in farms is evaluated upon the in-situ availability of bio-waste. Since daily manure production and final methane yield are extremely variable, calculations are done assuming mean values for the main variables (TS, SV, biogas yield, methane fraction and daily manure productivity per head). Then, extreme scenarios may be depicted considering lower and upper values from Table 2. Therefore, the average biogas potential is determined by aggregating all cattle/swine heads in each class and, then, levelized on the number of farms occurring in each class. Aggregated results are displayed in Table 4, showing the annual biogas productivity of farms extracted from different classes. Representative sizes have been determined as arithmetical average on the total amount of farm belonging to that class, according to regional stats (Table 3).

On average, cattle farms with less than 50 heads show a low daily biogas output, far from being profitable with an on-site plant, considering the state-of-the-art of micro-digester and micro-CHP from Table 1. The same comment is issued

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Table 3 – Cattle and swine farms in Umbria [26–28].

		Cattle			Swine	
		Beef	Dairy	Mixed		
Farms Number		2847	158	162	3614	
Total Heads (x100)		390	85	54	1772	
Heads distribution						
Domestic farms	<10 hd	72%	8%	47%	<100 hd	95%
Small farms	10–50 hd	23%	44%	42%	100–1000 hd	3%
Medium farms	50–100 hd	3%	24%	4%	1000–4000 hd	2%
Large farms	>100 hd	2%	24%	7%	>4000 hd	<1%

Table 4 – Farm-specific average biogas daily production. Results are levelized on the local number of farms. Equivalent electric power is calculated considering: i) an energy conversion efficiency of 30% typical of well-performing small-scale ICEs, ii) methane low heating value 35 MJ/Nm^3, iii) no-stop operation throughout the solar year.

Farm class	Beef Cattle			Dairy Cattle		
Hd	Arithmetic average	Biogas production	Equivalent electric power	Arithmetic average	Biogas production	Equivalent electric power
	Hd (LCE[7])	Nm^3/y	kW$_{e,eq}$	Hd (LCE)	Nm^3/y	kW$_{e,eq}$
<10	3	581	0.1	3	1232	0.2
10–50	24	5469	1.1	17	6672	1.3
50–100	68	15,336	2.9	50	19,459	3.7
>100	195 (113)	43,877	8.4	142 (142)	55,305	10.6

Farm class	Swine		
Hd	Arithmetic Average	Average biogas production	Equivalent electric power
	Hd (LCE)	Nm^3/y	kW$_{e,eq}$
<100	5	118	<0.1
100–1000	261	6602	1.4
1000–4000	1001 (65)	25,320	5.3
>4000	4001 (260)	101,203	21.1

Table 5 – Biogas daily potentiality for each farm type when manure and insilate are co-digested. Estimation of equivalent electric power are based on the average biogas yield.

Farm class	Beef Cattle			Dairy Cattle		
Hd	Arithmetic average	Average biogas production	Equivalent electric power	Arithmetic average	Average biogas production	Equivalent electric power
	Hd (LCE)	Nm^3/y	kW$_{e,eq}$	Hd (LCE)	Nm^3/y	kW$_{e,eq}$
<10	3	2453	0.4	3	5382	1.0
10–50	24	23,096	4.1	17	29,136	5.2
50–100	68	64,771	11.5	50	84,979	15.1
>100	195 (113)	185,316	33.0	142 (142)	241,519	43.0

Farm class	Swine		
Hd	Arithmetic average	Average biogas production	Equivalent electric power
	Hd (LCE)	Nm^3/y	kW$_{e,eq}$
<100	5	690	0.1
100–1000	261	38,497	6.9
1000–4000	1001 (65)	147,644	26.3
>4000	4001 (260)	590,133	104.8

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Table 6 – Case-study summary: energy and economic parameters.

Farm type	LCE	Yearly biogas Production	SOFC Micro-CHP Electric Power
		Nm^3/y	kW_e
BEEF >100 hd	113	43,877	14.6
DAIRIES >100 hd	142	55,305	18.4
SWINE >1000 hd	65	25,320	8.4
SWINE >4000 hd	260	101,203	33.7

for swine farms below 1000 heads. Conversely, cattle farms having more than 100 heads have a significant impact. The equivalent energy output estimated for a farm of 195 beef heads is 43,877 Nm^3/y, equivalent to 8.4 kW_e[8] whereas it rises to 55,305 Nm^3/y and 10.6 kW_e for dairy cattle farms. Then, regarding swine, farmholds with more than 4000 heads allow reaching a critical mass of manure and therefore a significant output in term of biogas (annual biogas output 101,203 Nm^3/y, equivalent to an electric power of 21 kW_e). Medium size cattle (50–100) and swine farms (1000–4000) show a borderline situation: yet, the applicability of micro digestion could be extended thanks to co-digestion. In fact, such farm classes represent a high biogas potential (as the distribution of animal heads Fig. 4 shows).

As a matter of fact, in many countries, co-digestion is often practised to increase the output power of the plant. Therefore, results from Table 4 are extended in the event of co-digestion of animal manure and corn insilate (by a weight co-digestion ratio of 40%). Related results are displayed in Table 5.

As expected, in this event also medium-scale cattle farms with 50–100 heads and medium scale swine farms with 1000–4000 heads allow overcoming the lower threshold of 7 kW_e (as the minimum defined for micro-CHP in biogas plants in the European frame [3]). Moreover, the electric potential of larger farms significantly grows.

Relevant case-studies

The total annual biogas potential embedded in cattle and swine waste in Umbria is about 67 GWh/y. Since regional farms account for 2% of the total cattle/swine heads in Italy, this result might be extended to 3.25 TWh/y regarding the national availability of biogas from such a source. This represents an increase of 10% with regard to the actual amount of biogas used in the country for both electricity and heat applications. This upgrade may grow, considering the scenario of co-digestion. Nonetheless, for a matter of farm size, only a share of the biogas energy potential can be exploited (i.e. domestic farming is excluded from the computation).

Data regarding Umbrian farms have been compared to European data in order to identify farm classes that are meaningful for the deployment of SOFC market. In comparison with the well-developed German biogas market [25], farms showing a statistical significance are pointed out. Most of bio-waste resources are allocated in swine farms with 1000–4000 heads (more than 30% of resources) bringing to equivalent electric capacity in the range 7 kW_e (in meat swine farms with 1000–2000 heads) – 14 kW_e in meat swine farms with 2000–4000 heads). Reproduction swine farms allow reaching 40 kW_e in plants with 1000–2000 heads.

Moreover, concerning beef/dairy cattle farms, the most relevant plants considering of bio-waste allocation are featured by a farm size from 50 to 500 heads, which bring to the same average range of equivalent electric power (respectively 7 kW_e and 14 kW_e, where the equivalent power is estimated only on the local availability of manure, considering the total distribution of cattle heads in beef and dairy farms).

In the followings, 4 types of livestock farms are assumed as relevant regional case-studies:

- Beef and dairy farms with more than 100 heads (from the data analysis reported in Table 4, the average regional dimension is 113 LCE and 142 LCE respectively);
- Swine farms with more than 4000 head (two cases are examined, namely 65 LCE and 260 LCE swine farms).

All the selected case-studies allow overcoming a minimum electric power output of 7 kW_e when SOFC micro-CHP generators are installed (the minimum power threshold is set as pointed out from the previous survey over biogas micro-plants). Just the case of manure digestion is analysed (no further investigation is made on co-digestion of manure and agricultural scrap/other energy crops). Details about the plant components sizing are given in the next section (see Table 6).

Energo-economics of SOFC in the agricultural/livestock market

SOFC vs ICE: gain energy and environmental performance

The utilization of a SOFC micro-CHP unit allows overcoming barrier in terms of micro-scale, as well as gaining much on efficiency. Fig. 5 reports the performance upgrade obtainable switching from ICE to SOFC in all of farm classes identified, considering an electric efficiency of 50% [34] in the entire plant capacity range. The 4 case-studies defined in the previous section are summarized in Table 6.

Economics of micro-CHP SOFC

Based on market data elaboration and the assumptions presented in Section Economic assessment, TCO and LCOE are calculated and shown in Fig. 6 for all case-studies.

For the average beef farm (about 15 kW_e), costs estimations in today market conditions reveal a TCO of 472 k€, corresponding to an LCOE of 0.392 €/kWh. In such market condition, the share of the SOFC CHP unit over the TCO is noteworthy, namely the 86% out of the total. Expenses related to the anaerobic digester section cover the 11% of the TCO, while sulphur clean-up accounts for 2%. Looking towards the complete market roll-out of SOFC–CHP generator, the "*industrialization*" scenario offers the following results: TCO 139 k€ (SOFC CHP share equal to 54%, Anaerobic digester 38%

[8] To establish the equivalent electric power of a given amount of biogas, the following assumptions are made: biogas-to-electricity energy conversion efficiency equal to 30% (typical of well-performing small-scale ICEs), methane low heating value 35 MJ/Nm3.

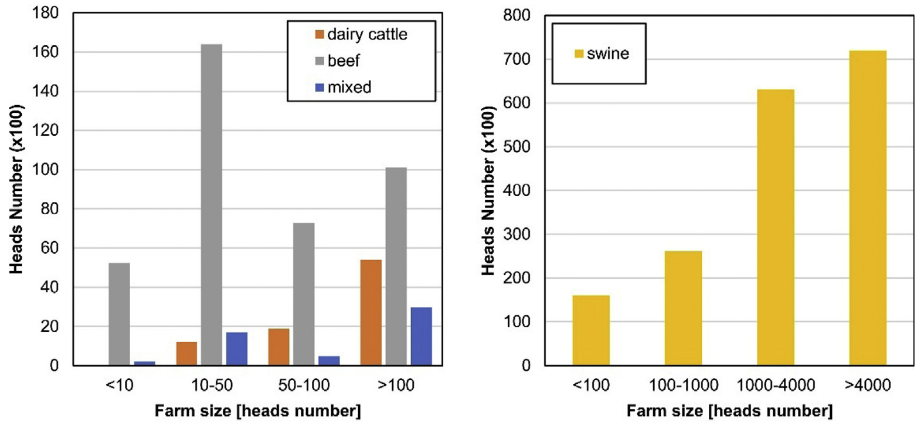

Fig. 4 – Distribution of cattle (left) and swine (right) heads according to the farm class.

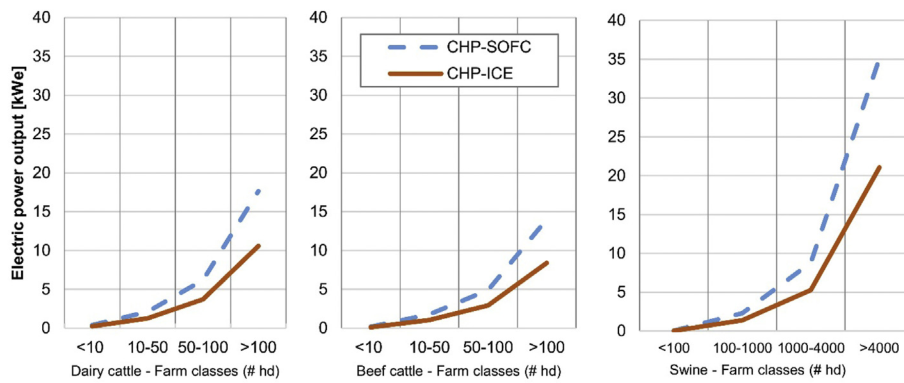

Fig. 5 – Electric efficiency in biogas CHP plants based on ICE and SOFC for dairy cattle (left), beef cattle (centre) and swine farms (right).

and Sulphur clean-up 8%) and LCOE = 0.116 €/kWh. Similarly, results concerning the other farms can be deduced from the plots in Fig. 6. Beside the TCO – whose order of magnitude varies in agreement to the plant biogas productivity – the specific cost of electricity produced (LCOE) assumes the values of 0.387 €/kWh, 0.204 €/kWh and 0.115 €/kWh, respectively in the "*today*", "*standardisation*" and "*industrialization*" fuel cell market scenario.

Discussion

Cattle and swine farms embed a significant share of the distributed renewable energy potential. In the region Umbria, assumed as investigation field for the scope of this research, most of cattle farms consist of a few hundred heads, while swine farms consist of a few thousand heads. This allows the realization of CHP plants with a maximum electric size of about 30 kW_e. Looking at the potential market existing in Umbria, some conclusions may be drawn for plants run in simple digestion (only livestock manure):

- There about 100 cattle farms which are eligible as customers for micro-scale digestion and CHP plants. Despite this number is small with regard to the total amount of farms registered in regional records, they embed the 38% of the biogas energy potential that can be recovered from cattle farms in Umbria;
- Similarly, there are roughly 20 swine farms eligible for the same purpose, which represent the 41% of the biogas energy potential related to this specific niche;
- Considering plants run in co-digestion (livestock manure + agriculture waste) the number of possible customers rises to 240 and 80 for cattle and swine farms respectively, covering a higher share of the unexploited regional biogas potential. In detail, this rises to 56% in the further case and 76% in the latter.

Besides the regional connotation of this study, the outcomes regarding the market segment to be covered may be extended to a European framework, where a similar statistic concerning the distribution of livestock heads and farms can be checked [25]. In addition to that, other studies regarding the US scenario confirm the relevance of small livestock farms to the end of energy production [9]. Within the identified market niche, SOFC modules from 10 kW_e to 35 kW_e would be required. In addition to that, more market opportunities may arise from the food supply chain, which produces much waste that can be converted into biogas with a suitable composition for SOFC operation [40].

For their operating conditions and the typical power range of commercially available products (c.a. tens of kW_e), SOFC is

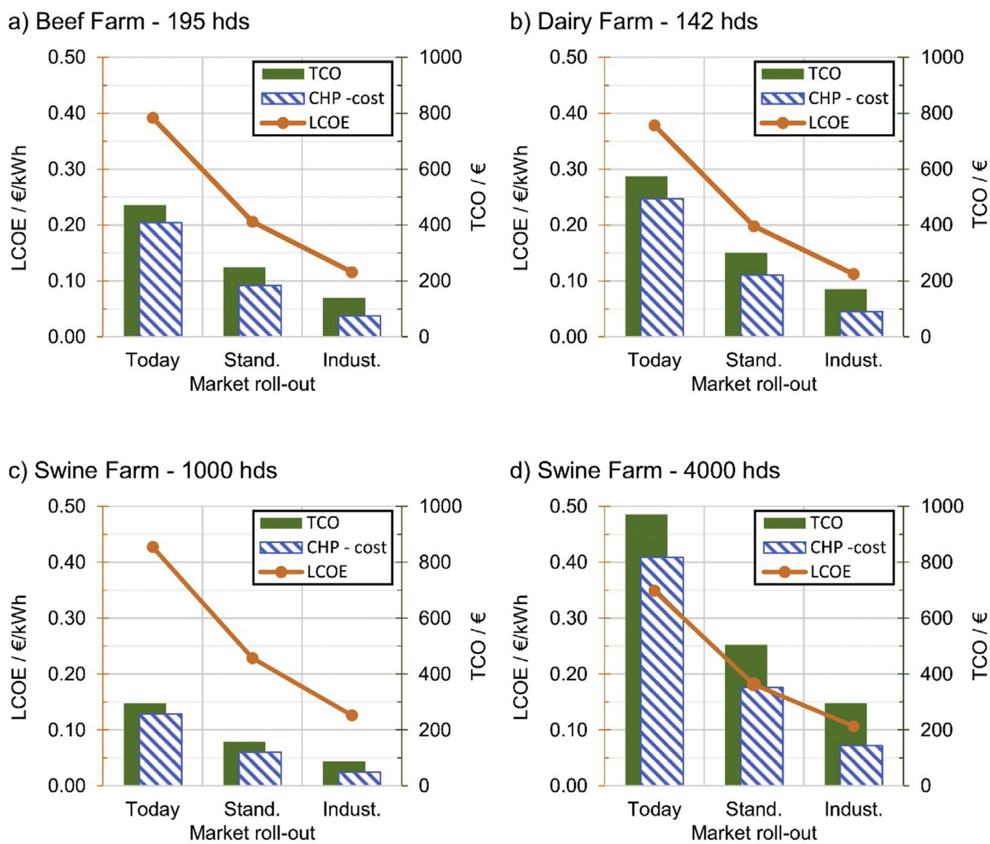

Fig. 6 – Cost estimation for micro-biodigester plants equipped with a SOFC–CHP unit: Total Cost of Ownership (TCO, €), Total costs of CHP (CHP – cost, €), Levelized cost of Electricity (LCOE €/kWh). Cost indicators for average livestock farm, according to Table 6 results: a) beef farm, b) dairy farm, c) swine farm, d) larger swine farm. Costs are depicted starting from today's market data and foreseeing the upcoming market roll-out (standardisation and industrialization of SOFC manufacture).

the ideal CHP technology to be installed in that market segment. This fact seems promising both for the creation of new markets for SOFC and for the exploitation of a significant share of renewable energy which is distributed in small sites.

However, the cost-effectiveness of this technological solution will be achieved as SOFCs production volume increases. As a matter of fact, SOFC micro-CHP will become a competitive alternative to other electricity generation technologies in micro, and small biogas plants when SOFC micro-CHP costs share is just 50% of the total TCO. Considering the unitary cost of electricity, this will end in an LCOE of 0.115 €/kWh, that is lower than the market parity level for electricity generation (about 0.21 €/kWh considering today's European energy framework data [41] and power generation costs from renewables as reported by IRENA [42] specifically for biogas plant below 1 MW).

In addition to that, the technological deployment of robust SOFC materials and simplified system architectures are key-points to achieve a higher durability of SOFCs and a favourable return of investment regarding the installation of the system as a whole. In order to reduce costs for the system installation, a great effort in the research is devoted to investigating the option to directly feed biogas to the SOFC without a complete external reformer [16]. Nonetheless, if capital costs globally decrease for a reduction in the number of system components, a more severe degradation rate is expected throughout the SOFC stack lifetime [18,43]. Thereby, this increases maintenance and replacement costs. Unfortunately, concerning direct biogas feeding to SOFC, only few experimental results are available. In most cases, experiments are performed on single cells (not on stacks) and are not referred to long-term tests, showing experimental evidence of cells tested for 500–1500 h. Degradation rates measured in this kind of test depict the status of the cells after the first hours of operation, hence they cannot be extended to forecast performance decay after several thousand hours. Nevertheless, since there is no consistent evidence of stack operation for long durations under direct biogas feeding, there is a lack of information to draw a complete techno-economic feasibility plan for advanced SOFC CHP system architectures. This call for advancements concerning experimentation.

Nowadays, the most sensible techno-economic evaluation for a micro-digestion system with a SOFC micro-CHP unit can be done with regard to commercial systems equipped with an external reformer. For such a system, it is also interesting to perform a comprehensive assessment of the environmental impact reduction in comparison to combustion-based technologies (Carbon emission balance, NOx). This part is out of the scope of the current paper, but it will be within the aim of further research.

Conclusions

In the present paper, the energo-economic feasibility study for SOFC micro-CHP introduction in livestock bio-digestion plants is presented. First relevant cases-study are defined from data elaborated from a regional survey. These represent typical livestock farms where one can install SOFC micro-CHP generators for the efficient conversion of in-situ produced biogas (cattle farms > 100 heads, swine farms > 1000 heads). The economic study reveals that, in today's market conditions, the share of TCO associated with SOFCs still hinders the feasibility of a similar system in small distributed plants. Nevertheless, thanks to an increase of SOFCs manufacture volume, future scenarios foresee improvements up to the attainment of electric market parity.

Since the outcomes of the regional survey show standard features with European and American data from the livestock sector, the validity of the results is finally extended to a widely international framework.

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Nomenclature

BDN	Banca Dati Nazionale
CHP	Combined Heat and Power
HD	Head
ICE	Internal Combustion Engine
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
ISTAT	Istituto Nazionale di Statistica
LCA	Life Cycle Assessment
LCE	Lactating Cow Equivalent
LCOE	Levelized Cost of Electricity
MSW	Municipal Solid Waste
NG	Natural Gas
NPV	Net Present Value
NOx	Nitrogen Oxides
POX	Partial Oxidation
PV	Photovoltaic
REF	Reforming
RES	Renewable Energy Sources
SOFC	Solid Oxide Fuel Cell
SotA	State-of-the-Art
SOx	Sulphur Oxides
TCO	Total Cost of Ownership
TS	Total Solids
VS	Volatile Solids

REFERENCES

[1] IEA statistics. 2019 [Online]. Available: https://www.iea.org/statistics/. [Accessed 28 August 2019].
[2] Scarlat N, Dallemand JF, Fahl F. Biogas: developments and perspectives in Europe. Renew Energy 2018;129:457–72.
[3] Hjort-gregersen K. Market overview micro scale digesters. 2015.
[4] AA.VV, "Atlante impianti GSE." [Online]. Available: https://atla.gse.it/atlaimpianti/project/Atlaimpianti_Internet.html. [Accessed: 20-Aug-2011].
[5] Torrijos M. State of development of biogas production in Europe. Procedia Environ Sci Jan. 2016;35:881–9.
[6] GSE, "Impianti a fonti rinnovabili grin." [Online]. Available: https://www.gse.it/servizi-per-te/fonti-rinnovabili/impianti-a-fonti-rinnovabili-grin. [Accessed: 01-Sep-2019].
[7] Gas engines - Jenbacher. 2019 [Online]. Available: https://www.clarke-energy.com/gas-engines/.
[8] Soland M, Steimer N, Walter G. Local acceptance of existing biogas plants in Switzerland. Energy Pol Oct. 2013;61:802–10.
[9] Klavon KH, Lansing SA, Mulbry W, Moss AR, Felton G. Economic analysis of small-scale agricultural digesters in the United States. Biomass Bioenergy Jul. 2013;54:36–45.
[10] Claudio F, Piccinini S. Biogas l 'analisi di fattibilità tenico-economica. C.R.P.A Not 2008;4:1–11.
[11] McPhail SJ, Conti B, Kiviaho J. The yellow pages of SOFC technology - international status of SOFC deployment 2017. 2017.
[12] Miyake M, Iwami M, Goto K, Iwamoto K, Morimoto K, Shiraishi M, Takatori K, Takeuchi M, Nishimoto S, Kameshima Y. Intermediate-temperature solid oxide fuel cell employing reformed effective biogas: power generation and inhibition of carbon deposition. J Power Sources 2017;340:319–24.
[13] Barelli L, Bidini G, Cinti G. Steam vs. dry reformer: experimental study on a solid oxide fuel cell short stack. Catalysts 2018;(1):1–12.
[14] Chiodo V, Galvagno A, Lanzini A, Papurello D, Urbani F, Santarelli M, Freni S. Biogas reforming process investigation for SOFC application. Energy Convers Manag 2015;98:252–8.
[15] Baldinelli A, Barelli L, Bidini G. On the feasibility of on-farm biogas-to-electricity conversion: to what extent is solid oxide fuel cells durability a threat to break even the initial investment? Int J Hydrogen Energy 2018;43(35):16971–85.
[16] Baldinelli A, Subotic V, Mondi F, Di Michele A, Barelli1 L, Bidini G. Quick degradation detection on biogas-fuelled SOFCs. ECS Trans 2019;91(1):1571–80.
[17] Takahashi Y, Shiratori Y, Furuta S, Sasaki K. Thermo-mechanical reliability and catalytic activity of Ni–Zirconia anode supports in internal reforming SOFC running on biogas. Solid State Ionics Oct. 2012;225:113–7.
[18] Shiratori Y, Ogura T, Nakajima H, Sakamoto M, Takahashi Y, Wakita Y, Kitaoka T, Sasaki K. Study on paper-structured catalyst for direct internal reforming SOFC fueled by the mixture of CH4 and CO2. Int J Hydrogen Energy Aug. 2013;38(25):10542–51.
[19] Shiratori Y. Biogas production from local biomass feedstock in the mekong delta and its utilization for a direct internal reforming solid oxide fuel 2017;5(May):1–8.
[20] Nguyen TGH, Sakamoto M, Uchida T, Doan DCT, Dang MC, Tu PH, Sasaki K, Shiratori Y. Development of paper-structured catalyst for application to direct internal reforming solid oxide fuel cell fueled by biogas. Int J Hydrogen Energy Apr. 2019;44(21):10484–97.
[21] Ammermann H, Hoff P, Atanasiu M, Ayllor J, Kaufmann M, Tisler O. Advancing Europe's energy systems: stationary fuel cells in distributed generation. 2015.

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[22] De Arespacochaga N, Valderrama C, Peregrina C, Mesa C, Bouchy L, Cortina JL. Evaluation of a pilot-scale sewage biogas powered 2.8 kW_e Solid Oxide Fuel Cell: assessment of heat-to-power ratio and influence of oxygen content. J Power Sources 2015;300:325–35.
[23] Bicer Y, Khalid F. Life cycle environmental impact comparison of solid oxide fuel cells fueled by natural gas, hydrogen, ammonia and methanol for combined heat and power generation. Int J Hydrogen Energy Jan. 2020;45(5):3670–85.
[24] Rillo E, Gandiglio M, Lanzini A, Bobba S, Santarelli M, Blengini G. Life cycle assessment (LCA) of biogas-fed solid oxide fuel cell (SOFC) plant. Energy May 2017;126:585–602.
[25] Scheftelowitz M, Thrän D. Unlocking the energy potential of manure-an assessment of the biogas production potential at the farm level in Germany. Agric For 2016;6(2).
[26] UOD Osservatorio Epidemiologico Umbria Izsum. L'allevamento suino in Umbria. 2016.
[27] UOD Osservatorio Epidemiologico Umbria Izsum. Allevamento bovino e bufalino in Umbria. 2014.
[28] Istat - consistenze degli allevamenti regione Umbria. 2019 [Online]. Available: http://dati.istat.it/. [Accessed 16 August 2019].
[30] Wasajja H, Lindeboom REF, van Lier JB, Aravind PV. Techno-economic review of biogas cleaning technologies for small scale off-grid solid oxide fuel cell applications. Fuel Process Technol Jan. 2020;197:106215.
[31] Pipatmanomai S, Kaewluan S, Vitidsant T. Economic assessment of biogas-to-electricity generation system with H2S removal by activated carbon in small pig farm. Appl Energy May 2009;86(5):669–74.
[32] Worawimut C, Vivanpatarakij S, Watanapa A, Wiyaratn W, Assabumrungrat S. Performance evaluation of biogas upgrading systems from swine farm to biomethane production for renewable hydrogen source. Int J Hydrogen Energy 2019;44(41):23135–48.
[33] Lanzini A, Ferrero D, Papurello D, Santarelli M. Reporting degradation from different fuel contaminants in Ni-anode SOFCs. Fuel Cell 2017;17(4):423–33.
[34] Saadabadi SA, Thallam Thattai A, Fan L, Lindeboom REF, Spanjers H, Aravind PV. Solid oxide fuel cells fuelled with biogas: potential and constraints. Renew Energy Apr. 2019;134:194–214.
[35] Baldinelli A, Barelli L, Bidini G, Di Cicco A, Gunnella R, Minicucci M, et al. Advancements regarding in-operando diagnosis techniques for solid oxide cells NiYSZ cermets. In: AIP (American inst. Physics) conference Proceedings; 2019.
[36] Lai CS, Mcculloch MD. Levelized cost of energy for PV and grid scale energy storage systems. Manuscr. sumbitted Publ; 2016. p. 1–11.
[37] IEA World Energy Outlook 2015, "2015 edition," 2015.
[38] Shelford AT, Gooch C, Hines M, Choudhury A, Felton G. Farmer's guide to dairy -derived biogas production, treatment and utilization. 2018. p. 1–78. no. 1.
[39] Cebolla O. Global deployment of large capacity stationary fuel cells. 2019.
[40] Hagen A, Langnickel H, Sun X. Operation of solid oxide fuel cells with alternative hydrogen carriers. Int J Hydrogen Energy 2019;44(33):18382–92.
[41] Eurostat. Eurostat - electricity prices statistics [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics. [Accessed 1 February 2019].
[42] IRENA International Renewable Energy Agency. Renewable power generation cost in 2017. 2018.
[43] Kushi T. Performance and durability evaluation of dry reforming in solid oxide fuel cells. Int J Hydrogen Energy Oct. 2016;41(39):17567–76.
[44] Wei M. Total cost of ownership modeling for stationary fuel cell systems. Berkeley; 2016.

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