INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–15

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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?

*A. Baldinelli**, *L. Barelli, G. Bidini*

Università Degli Studi di Perugia, Dipartimento di Ingegneria, Italy

ARTICLE INFO

Article history:
Received 4 August 2017
Received in revised form
2 February 2018
Accepted 5 February 2018
Available online xxx

Keywords:
Biogas
SOFC
Degradation
Direct feeding
Techno-economic feasibility
Payback time

ABSTRACT

Despite their promising features, adverse economic feasibility still hamper SOFCs wide implementation and this effect is emphasized as long as the system size is reduced. According to previous investigations, the biogas pre-treatment section represents a burden for the economic viability. Aiming at reducing the extent of installation costs in SOFC-based configurations, biogas partial upgrading through CO_2 gas-separation membranes is put forth as innovative solution against reforming. This innovative system concept is expected to make SOFCs more cost-effective, yet resulting feeding gas might cause a quicker SOFC performance decay. Besides solving this trade-off, the economic viability results strongly sensitive to subsidiary electricity prices in force according to the regulatory framework.

This paper presents a comparative economic assessment regarding biogas-to-electricity conversion via Solid Oxide fuel cells (SOFCs) and mature technologies as internal combustion engines (ICEs). Results highlighted that, the innovative SOFC system is far more viable than reforming-based one, exhibiting a reasonable payback time, with an adequate subsidized electricity sale price (4 and 5 years for small/medium and large-size plants respectively when subsidy is 0.28 €/kWh), up to $1\%_{1000h}$ degradation rate. On the other hand, whilst considering a SOFC degradation rate of $0.03\%_{1000h}$, the reforming-based system appears feasible only on large-size plants, yet recovering the initial capital expenditure in 9 years. Moreover, once the break-even point is reached, the gain in the net revenue produced by the innovative system is amplified in the event of small-size installation. This allows the possibility to undertake the risk of higher degradation rates (up to $2\%_{1000h}$) without jeopardizing the economic profitability. Therefore, in the present regulatory framework and under current capital costs projections, the innovative SOFC system appears as much profitable as ICE mature technology. Such effort in the design of the fuel pre-treatment unit can lever SOFC broad spreading into the market of small biogas producers.

* *Corresponding author.*
E-mail address: arianna.baldinelli@gmail.com (A. Baldinelli).
https://doi.org/10.1016/j.ijhydene.2018.02.031

Introduction

Energy efficiency and environmental protection are two pillars of the energy transition the contemporary society is accomplishing. Such ambitious global goals require as much effort from the few operators of large plants as from the many operators of small plants [1]. In particular, the latter gain relevance when renewable energy sources (RES) are concerned, for their intrinsic features (e.g. low energy density per mass/volume unit, energy potential spread on a wide territory), which make less attractive plants with a high primary resources consumption. In the latter case, biomass handling and transportation issues hinder the sustainability of the plant [2].

For this scope, the biogas supply chain appears promising: it is a RES energy-conversion pathway, it turns waste (manure, agricultural scrap, waste-water) into valuable products and its main output is a fuel gas which is suitable for both internal/external combustion engines [3] and for advanced devices, such as fuel cells [4]. Concerning the second option, Solid Oxide Fuel Cells (SOFCs) are the most promising technology [5], for their high fuel flexibility and high operative temperature enabling combined heat and power generation (CHP).[1] Furthermore, in opposition to both internal combustion engine (ICE) and gas turbines (GT), SOFCs energy-conversion efficiency is scarcely influenced by the system size.

In the scientific literature, economic analysis of conventional SOFC-based CHP system has been investigated in Ref. [6], showing a lengthy payback time (10 years) for residential cogeneration units operated in Hong Kong, out of the frame of biowaste-derived fuel. The application of SOFCs in biogas plants is investigated in other publications. For instance, a well-addressed market segment is represented by both waste-water treatment plants [7,8] and sewage-sludge treatment plants, for whom larger-size cogeneration units are required. In detail, in the recent work at [9], the viability of a SOFC cogenerator in a sewage sludge plant is analysed. Beside the primary need to shrink the capital expenditures (CAPEX) related to that cogeneration system, the conclusions of this paper stress that the viability of SOFC would be more predictable on small-size plants, based on an empirical induction regarding the expected increased production by fuel cell manufactures. Hence, notwithstanding the favourable scale-effect of capital costs as long the plant size grows, referring to current capital costs prediction, the investigation on small-size SOFC units seems to yield more reliable outcome. In addition to a mere question of data availability, taking benefit from the undeniable advantages of modularity and high efficiency, SOFCs do bear a major potential for high-efficiency on-farm electricity generation in the event of small enterprises.

Being equal the farm biogas capacity, the introduction of a SOFC generator (plus related balance of plant components) downstream the biodigester implies an increase in the CAPEX, though an increase of the yearly income due to the sale of larger amount of electricity as well. In conventional system configurations featuring an external reforming step, complex SOFC balance of plant and associated costs, hinder a deep penetration in those market areas. For that reason, either biogas direct feeding or a lean biogas pre-treatment [5,10–12] are worthwhile solutions, leading to simplified system configurations and the subsequent reduction of installation costs. Despite this, biogas - as it is after the removal of harmful minor components such as sulphides [13] – compromises long-term stability of SOFC materials when directly fed to the SOFC. Certainly, this reduces the useful lifetime of the fuel cell unit [14,15], asking for a frequent replacement of the core component of the system, which introduce an additional CAPEX item occurring recursively during the system lifespan. Moreover, SOFC direct exposure to biogas is expected to accelerate performances decay, hence negatively affecting the final energy output throughout the device lifetime and the related yearly income. Thus, it is correct to say that the system design not only affects energy efficiency but also economic performances. Following on from this, the economic feasibility becomes the real bottleneck for a widespread implementation of SOFCs.

Dealing with biogas utilization into SOFCs, in a previous work by the authors [16], the energy performances of an innovative biogas-to-electricity system were evaluated in comparison to a conventional reforming-based solution. On a steady-state approach, results showed that SOFC operation with partially upgraded biogas,[2] thanks to the introduction of a state-of-the-art upgrading device (namely, CO_2-separation membrane) is beneficial from the point of view of both first and second law efficiencies. Beyond system-level matters, SOFC materials tolerance to such feeding conditions (partially upgraded biogas without impurities) has been experimentally proved by the authors, revealing no sharp degradation after a 200-h exposure [17]. Whilst this outcome appears promising, it does not allow estimating correctly how fast SOFC performances decay after thousand-hour operation. Unfortunately, the scientific literature lacks long-term results concerning SOFC system operation under those feeding conditions.

When such a crucial information suffers from a wide uncertainty, it is hard to draw a realistic economic assessment associated to the SOFC system running on operating conditions different reference long-term durability tests. Hence, the economic assessment itself may be turned into an indirect tool to determine the upper threshold for acceptable degradation rate.

Opting for this kind of approach, the current work outlines an economic assessment of three biogas-to-electricity pathways when applied in farmholds with a different biogas capacity. In detail, they are: I) an ICE-based system representing the state-of-the-art choice, II) a SOFC-based system equipped with a biogas-reforming unit, and III) a gas-separation

[1] In an integrated biogas-fuel cell facility, heat recovery is useful for the thermal sustainment of the waste digestion process.

[2] The definition “upgraded biogas” refers to a gas mixture made by two major components: methane and carbon dioxide. The latter is present in smaller amounts compared to raw biogas exhibiting a carbon dioxide content in the range of 30–50%$_{vol.}$ The reduced fraction of carbon dioxide is the result of a lean upgrading process. In this sense, one should not use the definition “bio-methane”, since this implies that the upgrading process has been pushed to the carbon dioxide separation efficiency required by substitute natural gas standards [18].

Please cite this article in press as: Baldinelli A, et al., 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?, International Journal of Hydrogen Energy (2018), https://doi.org/10.1016/j.ijhydene.2018.02.031