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Preliminary design of AR/SOFC cogeneration energy system using livestock waste

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Abstract

This paper reports on a sizing procedure for integrated Anaerobic Reactor/Solid Oxide Fuel Cell cogeneration energy system powered by livestock waste, in order to meet the provisions of Industry 4.0, connected to the new paradigm of Agriculture 4.0. The algorithm accounts on two main computational blocks, associated to the biogas production plant and to the SOFC energy unit respectively. A numerical modeling is performed to dimension the anaerobic digester and the biogas production deriving, as well as to dimension the energy unit and determine its techno-energy performance when it is fed by the previous biogas.
An application of the algorithm is made to a mid-size livestock farm, in order to valorize the biomass waste produced in situ.

Keywords: SOFC; Biomass; Biogas; Cogenerative Plant; Anaerobic Digester.

1. Introduction

Integrated systems Anaerobic Digester (AR)/Solid Oxide Fuel Cell (SOFC) are the subject of intense research and development (R&D) activity, aimed to further improve the performance of these devices, to reduce their production costs and to start spreading them on a larger scale [1-10]. Such a combination of technologies can count on the energy recovery, as well as valorization, of biomass considered a burden to be disposed of with related costs. Moreover, the strength of the SOFC is that of high energy efficiency and of the particular propensity towards biofuels, which make acquire them a key role in the "green and clean technologies - from waste to energy chain" [11-15]. Anaerobic digestion is a biochemical process of degradation of wet organic material in an oxygen-free environment. The products are digestate and biogas. The latter is a gas composed mainly of methane and carbon dioxide, with small percentages

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of ammonia, hydrogen, nitrogen, and trace sulfur compounds. Biogas can be used in various energy sectors with beneficial environmental developments in the circular economy. Currently, biogas plants with an electrical power of up to 300 kW are incentivized in Italy by DL Milleproroghe [16]. A particular use of biogas concerns its subsequent conversion into biomethane, currently heavily sponsored [17] and strongly encouraged as a biofuel for current propulsion systems, achieving important positive impacts on the environment in terms of CO_2 emissions. In fact, the supply of biomethane produces 33 $g_{CO2,eq}$/km vs 156 $g_{CO2,eq}$/km produced by diesel fuel [18-19]. Greenhouse gas emissions can be further reduced through actions aimed at reusing digestate as fertilizer and reducing the distance between the place of production of raw materials and the biomethane production plant. The production potential of biomethane estimated by the "Consorzio Italiano Biogas" (CIB) is 8 billion Sm^3 in 2030. On the basis of the previous premises and perspectives, the new paradigm of "Agriculture 4.0" is now reality, such that the CIB issues the certificate of "biogas done well" [20]. The energy potential of biogas is strongly taken into account in the various studies developed by researchers around the world as supply gas for SOFC systems [21-26]. Many have investigated the biogas supply in SOFC, predicting high performance, often discussing methods to avoid technical problems with the anode electrode of the fuel cell [27-29]. Other researchers focus on different engineering layout such as anodic and cathodic recycling for improving performance [30]. In the future envisioned by Industry 4.0 and Smart Manufacturing, the data relating to the above integrated energy systems will be analyzed to improve efficiency. In order to put into effect a possible and conceivable future large-scale production, it is fundamental to analyze the AR/SOFC systems efficiencies as a function of the main parameters involved. This paper concerns on a sizing procedure for the design of integrated Anaerobic Reactor/Solid Oxide Fuel Cell cogeneration energy system powered by livestock waste. A numerical modeling is performed to dimension the anaerobic digester and biogas production deriving; as well as to dimension the SOFC energy unit and determine its techno-energy performance when fed by the previous biogas. This system represents an energy advancement with respect to the state of play of the current technology of Internal Combustion Engine, according to the expectations on energy efficiency and environmental sustainability. This study is aimed at finding the solution set for operating the integrated system in order to link the main parameter to Industry 4.0 and Smart Manufacturing concepts.

2. AR/SOFC plant scheme

Figure 1 illustrates the simplified AR/SOFC plant scheme. Biomass is properly collected and organized in the substrate, before being loaded into the anaerobic plant.

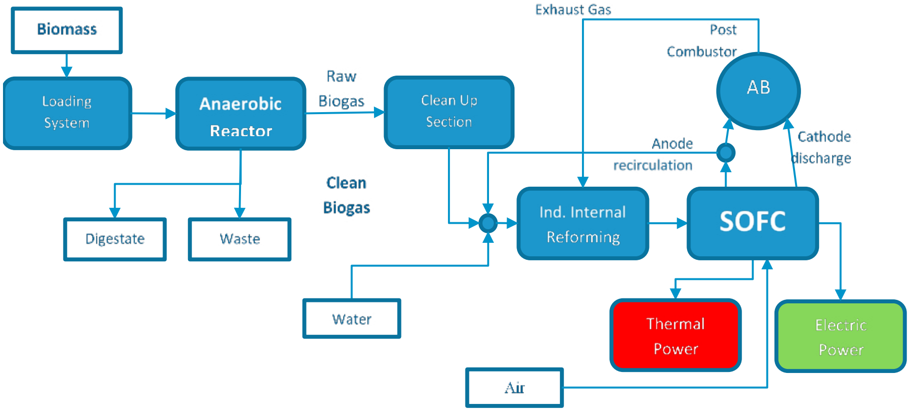

Fig. 1. Simplified AR/SOFC plant scheme.

The degradation of the organic substances, owing to micro-organisms, produces process waste, digestate that can be used as fertilizer, and biogas. The latter is composed of mainly methane and carbon dioxide, with impurities as hydrogen sulfide with other compound traces. Biogas is therefore upgraded in a proper section to then be used for energy purposes. Biogas is then enhanced in the SOFC cogeneration unit, where is mixed with steam and a part of anodes exhaust gases, first converted into a gas richer in hydrogen in Indirect Internal Reformer (IIR) and subsequently converted into electric and thermal powers, together with cathodic air in the SOFC stack. The non-recirculated anode exhaust gases are totally oxidized in an after burner (AB) with the cathodes exhaust gases to enrich the thermal content.

Feeding biogas, water and air are preheated from their feeding temperatures to their inlet temperature in SOFC stack in a heat exchanger, thanks to transfer of the thermal energy of the after burner exhaust gases.

3. Plant mass and energy balance

Anaerobic digester - The substances entering the process are represented by the basic substrate (sub), co-ferments and process water (H_2O). The flow of outgoing substances instead includes digestate (dig), biogas, and process water. Equation (1) presents the mass balance.

$$\dot{m}_{sub} + \dot{m}_{H_2O} = \dot{m}_{biogas} + \dot{m}_{H_2O} + \dot{m}_{dig} \qquad (1)$$

Energy unit - The substances entering the energy unit are biogas and water, representing the anodic stream, while air feeds the cathode compartment. Biogas and water are then mixed with anode exhaust gases. The residues of the energy process are high temperature exhaust gases (exh_gas), whose mass flow corresponds to the sum of the inlet flows (biogas, water, air), as in equation (2).

$$\dot{m}_{biogas} + \dot{m}_{H_2O} + \dot{m}_{air} = \dot{m}_{exh\_gas} \qquad (2)$$

Table 1 well expresses the overall molar balances for the Indirect Internal Reformer SOFC (IIR SOFC) [26]:

Table 1. Molar balance for SOFC energy unit

Section process	Reaction	Molar Balance
Indirect Internal Reformer		
Steam Reforming **Water Gas Shift**	$CH_4 + H_2O \leftrightarrow CO + 3H_2$ (3) $CO + H_2O \leftrightarrow H_2 + CO_2$ (4)	$F_{i,out,iir} - F_{i,in,iir} = \sum_{j=3,4}(\nu_{i,j} \cdot F_j)$ $with\ F_3 = F_{CH_4,sr,iir},\ F_4 = F_{CO,wgs,iir}$ (2a) $and\ i = CH_4, H_2O, CO, CO_2, H_2, N_2$
SOFC energy core		
Hydrogen oxidation (Anode site) **Carbon Monoxide oxidation (Anode site)**	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$ (6) $CO + O^{2-} \rightarrow CO_2 + 2e^-$ (7)	$F_{i,out,a} - F_{i,in,a} = \sum_{j=3,4,6,7}(\nu_{i,j} \cdot F_j)$ $with \begin{cases} F_3 = F_{CH_4,sr,a},\ F_4 = F_{CO,wgs,a}, \\ F_6 = F_{H_2,b},\ F_7 = F_{CO,b} \end{cases}$ (2b) $and\ i = CH_4, H_2O, CO, CO_2, H_2, N_2$
Anode recirculation		$F_{i,rec,iir} = f_{rec} \cdot F_{i,out,a}\ ;\ i = H_2O, CO, CO_2, H_2, N_2$
Fuel Utilization factor		$U_{f,conv} = \frac{F_{CO,b} + F_{H_2,b}}{4 \cdot F_{CH_4,bio}}$ (8a)
Oxygen reduction (Cathode site)	$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-}$ (8)	$F_{i,out,ca} - F_{i,in,ca} = \nu_{i,8} \cdot F_8$ $with\ F_8 = F_{O_2,b}\ and\ i = O_2, N_2$ (2c)

$\boldsymbol{\nu_{i,j}}$: stoichiometric coefficient; $\boldsymbol{F_{CO,wgs,iir}}$, $\boldsymbol{F_{CH_4,sr,iir}}$: CO and CH_4 molar flows converted into H_2 and CO inside IIR; $\boldsymbol{F_{CO,b}}$, $\boldsymbol{F_{H_2,b}}$: molar flows of CO and H_2 consumed by electrochemical anodic reactions; $\boldsymbol{F_{CO,wgs,a}}$, $\boldsymbol{F_{CH_4,sr,a}}$: molar flows of CO and CH_4 converted into H_2 and CO at the anode; $\boldsymbol{F_{CH_4,bio}}$: molar flow of methane in biogas; $\boldsymbol{F_{O_2,b}}$: molar flow of O_2 consumed by electrochemical cathode reaction; $\boldsymbol{F_{i,rec,iir}}$, $\boldsymbol{f_{rec}}$: recirculation molar flow and factor.

The analysis of the energy balance of the plant has the aim of quantifying the useful energy, net of consumptions associated to the different phases: transport (fresh biomass), pre and post treatments, digestion and disposal of process residues. The AR/SOFC Plant Energy balance for each plant element and section is given in Table 2.

Biomass collection and transport - The energy consumption associated to the transport of fresh biomass to the plant is calculated on the basis of the distances between the production sites and the treatment plant.

Electric consumption - This parameter is associated with the total amount of electricity required for the management of the plant, from the pre-treatment of the biomass to its movement inside the reactor, to the power supply of the control and management room. The overall consumption is equal to the sum of the self-consumed electric energy (produced by the system), in case taken from the external network. For example, this energy parameter is associated to typical electric auxiliary devices as pump, mixer mover and fan.

Thermal consumption - The anaerobic digestion process of biomass requires thermal energy to keep the reactor at a temperature suitable for the growth of bacterial fauna (mesophilic/thermophilic environment: about 40-50 ° C). This rate is recovered from the internal energy cycle, possibly integrated through integration boilers. Considering the plant

fully operational, the power required by the digester to maintain temperature is equal to that dispersed in the atmosphere by thermal exchange. Heat is made available in the form of water heated to approximately 90 °C, in case integrated by proper externally fed boilers.
Transport of process residues - Digestate leaving the digester, and substances separated from the biomass entering the initial pre-treatment phases (e.g., sand, grating, etc.) are considered among the process residues. The produced digestate is then transported inside the company perimeter or to the same breeders of the consortium company for the next scattering.
SOFC energy production - SOFC cogeneration unit is demanded for electric and thermal power production. Biogas is electrochemically converted (Table 1) producing electric power (Table 2). The high temperature condition makes possible to recover the thermal power possessed by the exhaust gases leaving the fuel cell. The recovered heat is largely self-consumed by the system. Excess heat is used according to the transfer to the district heating network.

Table 2. AR/SOFC Plant Energy balance

Anaerobic Digester Energy Needs Element		**Energy Unit Production Section**	
Electric Power Consumption			
Pump	$P_{pump}^{el} = \frac{\rho \cdot g \cdot Q \cdot H_{pump}^{m}}{\eta_{pump}}$	**Compressor**	$P_{Comp}^{el} = \frac{1}{\eta_{Comp}} \cdot \frac{k}{k-1} \cdot \frac{\Re}{MW} \cdot T_{in} \cdot (1-\beta^{\varphi})$
Mover/Mixer	$P_{mov/mix}^{el} = \frac{C_m \cdot \omega}{\eta_{mov/mix}}$	**SOFC Electric Power**	$P_{SOFC}^{el} = n_c \cdot V_c \cdot j_c \cdot A_c$
Fan	$P_{fan}^{el} = \frac{\rho \cdot g \cdot Q \cdot H_{fan}^{m}}{\eta_{fan}}$	**SOFC Thermal Power**	$P_{SOFC}^{th} = \dot{m}_{gas,out,B} \cdot \int_{T_{gas,out,eu}}^{T_{gas,out,HE}} c_{p,gas,out,B}(T)dT$
Thermal Power Consumption		**Net Energy Unit Electric Power**	$P_{eu}^{el} = P_{SOFC}^{el} - \sum P_{aux}^{el}$
Digest thermal transfer	$P_{req,da}^{th} = H \cdot A \cdot (T_{da} - T_{env})$	**Net Energy Unit Thermal Power**	$P_{eu}^{th} = P_{SOFC}^{th} - \sum \frac{P_{aux}^{th}}{\eta_{hc}}$
Thermal Power yielded by Energy Unit	$P_{yield,eu}^{th} = \eta_{hc} \cdot \left[\dot{m}_{H_2O} \cdot c_{p,H_2O} \cdot \left(T_{90} - T_{out}^{H_2O}\right)\right]$	**Energy Unit Electric Efficiency**	$\eta_{el,eu} = \frac{P_{eu}^{el}}{\dot{m}_{bio} \cdot LHV_{bio}}$
Integration Power	$P_{int}^{th} = P_{req,da}^{th} - P_{yield,eu}^{th}$	**Energy Unit Thermal Efficiency**	$\eta_{th,eu} = \frac{P_{eu}^{th}}{\dot{m}_{bio} \cdot LHV_{bio}}$
		Balance Electric Power	$P_{eu}^{el} = \sum P_{aux}^{el} + \sum P_{user}^{el}$
		Balance Thermal Power	$P_{eu}^{th} = \sum \frac{P_{aux}^{th}}{\eta_{hc}} + \sum \frac{P_{user}^{th}}{\eta_{hc}}$

$\boldsymbol{n_c}$: number of fuel cells; $\boldsymbol{V_c}$: fuel cell voltage; $\boldsymbol{j_c}$: el. current density; $\boldsymbol{A_c}$: active surface; $\boldsymbol{\dot{m}_{bio}}$ and $\boldsymbol{LHV_{bio}}$: mass flow and low heating value of biogas; $\boldsymbol{\dot{m}_{gas,out,B}}$ and $\boldsymbol{T_{gas,out,eu}}$: after burner exhaust gases mass flow and temperature; $\boldsymbol{T_{gas,out,HE}}$: temperature of final exhaust gas (403.15 K); $\boldsymbol{\eta}$: efficiency; ***aux:*** auxiliary devices.

3.1 Calculation Method

Anaerobic Digestion - The numerical modeling activity for the anaerobic process is set on a resolutive approach according to Buswell model (3).

$$C_aH_bO_cN_dS_e + \left(\frac{4a-b-2c+3d+2e}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d-2e}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d+2e}{8}\right)CO_2 + dNH_3 + eH_2S \quad (3)$$

The model considers the degradation of an organic substance consisting of C, H, O, N, S into methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3) and hydrogen sulphide (H_2S). The bio-chemical characterization is necessary in order to then dimension the reaction volume and determine performance parameters, as biogas production and efficiency, as in Table 3.

Table 3. Anaerobic Digester performance parameters

Total Volatile Solids	$TVS = TVS_{\%} \cdot TS_{\%} \cdot \dot{m}_{sub}$	Substrate Volumetric Flowrate	$\dot{V}_{sub} = \frac{\dot{m}_{sub}}{\rho_{sub}}$
Reactor Volume	$V_{react} = \frac{TVS}{OLR}$	Hydraulic Retetntion Time	$HRT = \frac{V_{react}}{\dot{V}_{sub}}$
Specific Gas Production	$SGP = 0.498 - 0.139 \cdot OLR$	Biogas Volumetric Flowrate	$Q_{biogas} = SGP \cdot TVS$

SOFC unit -The calculation tool developed in [26] is used to identify the best operative condition of the SOFC energy unit in terms of electric and thermal efficiencies at varying of anode exhaust gas recirculation factor, f_{rec}, and conventional fuel utilization factor, $U_{f,conv}$. If the produced biogas is used to satisfy the user electric load as much as possible, the SOFC energy unit has to operate in the maximum electric efficiency condition. In this condition the SOFC stack is sized. The thermal power produced by the SOFC energy unit partially satisfy the user thermal load, as following the electric contribution. Clearly, the powers served are net of internal absorptions for plant self-sustenance.

3.2 Calculation Flowcharts

Anaerobic Digestion – The calculation is based on an iterative cycle that must come to verification (Figure 2 (a)).
The starting data is the quantity and the quality of the amount of organic substrate to be processed in the digester: therefore the elemental composition of the waste (C, H, O, N, S), the content of total solids (TS) and total volatile solids (TVS). According to the plant technology chosen, that is strictly linked to the biomass, the Organic Load Rate (OLR) is set. The verification criterion is based on the Hydraulic Retention Time (HRT) which must necessarily be in the known experimental range. If verification is not attained, the calculation model recycles with of a new value of OLR. Finally, reactor volume, biogas volumetric flowrate, composition and process efficiency are calculated.
SOFC Energy Unit – The calculation procedure (Figure 2 (b)) starts with the definition of the main input parameters, such as biogas composition, variation ranges of the investigated parameters (anode exhaust gas recirculation factor, f_{rec}, and of the conventional fuel utilization factor, $U_{f,conv}$) and user electric and thermal needs. The calculation tool defines the model equations for each pair of f_{rec} and $U_{f,conv}$ values and the solver provides for their resolution [26]. The electric service is set on operating SOFC at maximum electric efficiency, so as to cover as much as possible the electric loads. The electric and thermal powers produced by a single fuel cell element are hence calculated. Finally, the SOFC stack is sized in terms of the number of fuel cells, and the net electrical and thermal supplies produced in relation to the user needs are monitored. After model convergence, the energy balance of the entire plant can be computed.

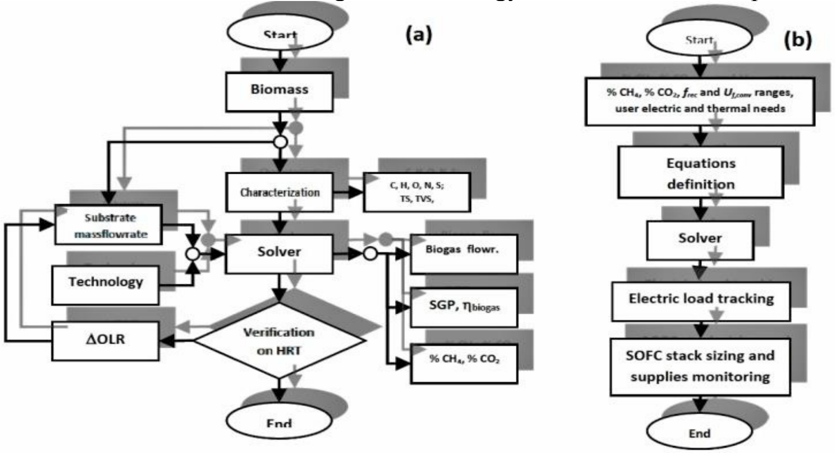

Figure 2. Calculation flowcharts: Anaerobic Digestion (a); SOFC Energy Unit (b).

4. Case study

This paragraph presents the application of the above procedure. The case study refers to a mid-size livestock farming. The main purpose of the company is the production of dairy products, therefore it breeds 250 cattles. Part of the buildings, falling within the company perimeter, are used as offices for administration and management purposes and as stores for company products selling, occupying a surface of 17400 m^2. A space is also occupied for 150 m^2 by a family, with guardian role. The livestock has to dispose 23200 kg of manure per day.

4.1 Anaerobic Reactor dimensioning

The substrate is based on exploiting the manure (73.3 %) produced by the cattles. With the purpose of generating biogas, the company also cultivates corn (8.5 %). Other substances, as triticale (8.5 %), poultry manure (1 %), olive

pomace (1 %), pellets of bran (5.9 %), mushroom waste (1.7 %) are taken from outside to enhance the mash to be fed to the reactor. For reasons of synthesis, the bio-chemical features of the organic substances are omitted.
The biomass waste produced inside the company perimeter together to that retrieved from outside furnish about 32 ton/day. The calculation algorithm calculates 1780 m^3/day of biogas, with methane volumetric content of 53.57 %. A volume of reactor of 1310 m^3, with a diameter of 15 m, is functional to this purpose. 4 cycles for biomass loading/digestate removal are foreseen to manage well the biomass. About 29 ton/day of digestate are present as process solid/liquid discharge.

4.2 Energy Balance

Table 4 reports the Plant Energy Balance, considering auxiliary devices and transportation for fresh biomass and process waste with the associated energy needs. Mixers, movers and pump are necessary for the functioning of the plant. A pre-tank is necessary to collect the original manure, that is then sent to the main loading tank, before feeding the digester. The digestate is post-treated to serve as fertilizer, while the biogas is cleaned-up before being valorized in the energy unit. The auxiliary devices need 55.55 kW of electric power, and 76.5 kW of thermal power, for respectively 267 MWh/year and 670 MWh/year. 1919 l/year of diesel fuel are necessary for fresh biomass provision, and 1220 l/year for solid digestate scattering on the fields presents in the company perimeter (2 ha). By considering the biogas production over the fuel for transportation, the gain is 445.5 kg_{biogas}/kg_{diesel}. The overall energy expense associated to fuel consumption is about 31 MWh/year. The net electric and thermal power produced by the energy unit is about 100 kW (876 MWh/year) and 97.5 kW (854 MWh/year), respectively.

Table 4. Plant Energy Balance

Plant Section	**Energy needs**
SOFC Energy Unit	
Operative temperature and pressure	973.15 K and 1 atm
Steam to Carbon ratio (S/C)	2
Air and water inlet temperatures	298.15 K
Fuel cells number	1825
Total gross electric power [kW]	126
Total gross thermal power [kW]	177.2
Total net electric power [kW]	99.55
Total net thermal power [kW]	97.46
Anaerobic Digestion Section	
Total Electric Power required [kW]	55.55
Total Electric Energy required [kWh/year]	267346.075
Total Thermal Power required [kW]	76.5
Total Thermal Energy required [kWh/year]	670140
Fuel and energy consumption for biomass and waste transportation	
Biomass provision from outside: Fuel consumption [l/year]	1919
Biomass provision from outside:Fuel energy consumption [kWh/year]	18902.15
Digestate scattering: Fuel consumption [l/year]	1200
Digestate scattering : Fuel energy consumption [kWh/year]	11820

4.3 Energy coverage (Energy Unit)

Figure 3 show the trends of the SOFC system electric (a) and thermal efficiencies (b), $\eta_{el,eu}$ and $\eta_{th,eu}$, at varying of the anode exhaust gas recirculation factor, f_{rec}, and conventional fuel utilization factor, $U_{f,conv}$. A deep analysis was necessary to find out the most favorable operating conditions. The maximum value of $\eta_{el,eu}$ is found as about 0.32 for f_{rec} of 0.32 (f_{rec}^*) and $U_{f,conv}$ of 0.65. The maximum value for $\eta_{th,eu}$ is found as 0.56 for f_{rec} equal to f_{rec}^* and $U_{f,conv}$ equal to 0.55. The same figure also illustrates the energy service in relation to the energy needs of the user, based on the typical winter (c) and summer (d) days, considering the net electric and thermal power supplies by the energy unit. In the winter day, the electric need is almost constant and close to 99.5 kW with two small exceptions between 7 and 9 hours and between 19 and 23. In the summer day, the electric need is near to 99.5 kW with a maximum deviation of about 4.5 kW at 22 hours. In the winter day, the thermal need is between 107 kW and 113 kW with two exceptions between 1 and 4 hours and between 22 and 24, where it is close to 99.5 kW and it is decreasing to 99.5 kW. In the summer day, the thermal need is between to 99 kW and 100.5 kW. The SOFC stack dimensioning revealed the necessity of organizing 1825 fuel cells. Almost all the electric need is satisfied except for a small electric power integration of about 2 kW in the typical winter day and for another electric power integration of about 4.5 kW in the typical summer day. The thermal power of 97.5 kW is not sufficient to cover the user need.

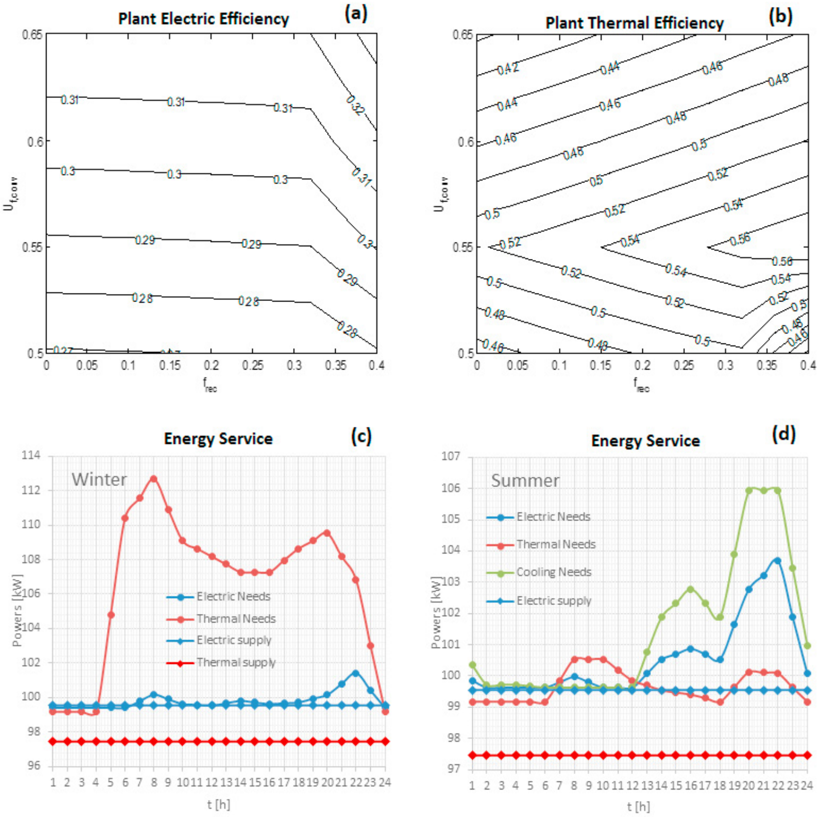

Figure 3. Electric and thermal efficiency of AR/SOFC system unit at varying of the anode recirculation factor, f_{rec}, and the conventional fuel utilization, $U_{f,conv}$; Electric and thermal needs and supplies for the user

5. Conclusion

The paper has concerned on a computational procedure for the design of integrated Anaerobic Reactor-Solid Oxide Fuel Cell cogeneration energy system powered by livestock waste from the perspective of Industry 4.0. The drawing up of plant energy balance has represented the starting point to have clear all the energy flows and to perform its dimensioning. The anaerobic digester was dimensioned by making use of a numerical modeling. An application of the algorithm was made to a mid-size livestock farm, in order to valorize the biomass waste produced in situ instead of simply disposing of them, thus satisfying the energy user needs. Accounting on mainly internal provision of biomass, a 1310 m^3 anaerobic digestion plant was sized, producing 1780 m^3/day of biogas with methane volumetric content of 53.57 %. 267 MWh/year of electric energy and 670 MWh/year of thermal energy were calculated as sustaining the biogas plant functioning. As for the SOFC energy unit (sized with 1825 fuel cells), the calculation tool was used to identify the best operative conditions at varying of anode exhaust gas recirculation factor, f_{rec}, and fuel utilization factor, $U_{f,conv}$. In nominal operating range ($0.5 \leq U_{f,conv} \leq 0.65$; $0 \leq f_{rec} \leq f_{rec}^*$) the maximum values of $\eta_{el,eu}$ and $\eta_{th,eu}$ were respectively about 0.32 ($f_{rec} = f_{rec}^*$ and $U_{f,conv} = 0.65$) and 0.56 ($f_{rec} = f_{rec}^*$ and $U_{f,conv} = 0.65$). The energy service was set on covering the electric load as much as possible. The problem studied well fits the theme of the circular economy implying a production and consumption model that involves sharing, lending, reusing, and recycling products. The solution carried out by the procedure can represent an input set for driving Industry 4.0 and smart manufacturing in this field, given the high expectation.

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