Optimal Control Strategy for Mixed Fuel Use in a Renewable Polygeneration System

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Keywords: Polygeneration Systems, Cogeneration, Renewable Energy Systems, Feedback Control Strategies, Energy Storage.

Abstract: The proposed work aims to analyse an optimal control strategy applied to a polygeneration system based on a gasification unit, an anaerobic digester and an alkaline electrolyzer to meet the fuel demand of an internal combustion engine. The purpose of the studied system is to meet the electricity and thermal energy demand of several end-users. The focus of this paper is on the fuel management strategy for a 2 MW cogenerator used to meet both these demands for a hospital. In the proposed model, the fuel injected into the internal combustion engine is a mixture of gaseous flows produced by renewable energy systems. The mixture is first composed of biogas, produced by an anaerobic digester fed by organic urban wastes. Secondarily, hydrogen obtained from the electrolysis of water through a 2 MW alkaline cell is considered. In addition, syngas produced by a 1.7 MW allothermal downstream gasification unit is adopted with different gasifying agents considered, including oxygen produced by the alkaline electrolyzer. Results show that with the adopted strategy, the fuel energy demand is met by 15% by biogas, 3% by hydrogen, 45% by syngas using oxygen as gasifying agent and 37% by syngas using steam as gasifying agent.

1 INTRODUCTION

The adoption of energy management strategies to reduce the energy consumption in several sectors is becoming an increasingly relevant issue (Nassar, 2023). Residential, industrial, commercial buildings as well as the transport sector require energy in form of power, heat, cool, and fuels (Papadis and Tsatsaronis, 2020). In most cases, these demands are still met through fossil fuels technologies that result in greenhouse gases emissions (Zhang, 2022). The integration of renewable energy based technologies is pivotal to prevent the energy systems from being increasingly climate affecting (Lima, 2020). Renewable technologies are, however, characterized by low energy density income and require optimal control strategies (Dalala, 2022). Studying different strategies for managing the energy flows produced by renewable sources is therefore crucial (Khan, 2022). Mostly, is important to adopt energy storage strategies to adequately exploit the fluctuating energy vectors incoming from solar energy (Calise, 2019).

The need for optimum management is especially significant for polygeneration systems, i.e. systems based on renewables and capable of meeting more than three different energy demands (Khoshgoftar Manesh, 2022). In case of residential applications, the production of domestic hot water is considered as additional demand (Gesteira, 2023). Studies on hybrid polygeneration systems are increasingly studied (Pipicelli, 2023). For residential applications, renewable energy systems are commonly based on solar energy (Kasaeian, 2020). In particular, for meeting the demand for domestic hot water, solar thermal collectors (STC) and photovoltaic-thermal collectors (PVT) are often investigated (Calise, 2022). In many cases, these studies contain energy and thermoeconomic analyses (Ceglia, 2020). In (Calise, 2020) the authors proposed a thermo-economic analysis of three water-energy-nexus

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Cimmino, L., Burgos, J. and Eicker, U.
Optimal Control Strategy for Mixed Fuel Use in a Renewable Polygeneration System.
DOI: 10.5220/0012000200003491
In *Proceedings of the 12th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2023)*, pages 70-78
ISBN: 978-989-758-651-4; ISSN: 2184-4968

polygeneration systems for the production of energy and desalinated water for two Mediterranean islands. The layouts of the different configurations are developed in TRNSYS to perform dynamic simulations. Details of the electric, thermal, cooling, and freshwater loads are provided by means of the TRNBuild add-on which allows to simulate the building behaviour. The three layouts are based, respectively, on concentrating PVTs (CPVTs) and electric chillers, PV modules with heat pumps, and CPVTs equipped with reverse osmosis units. The one that gave best results in terms of economic feasibility is the system based on completely electricity driven technologies.

For industrial applications, biomass driven polygeneration systems are paving the way for the production of clean fuels (Tabriz, 2023). Using different biomasses allows one to produce several biofuels (as hydrogen, bioethanol, or biodiesel) which can be exploited for different applications (Seo, 2022). Gasification and pyrolysis are the most studied processes for syngas production from biomass (Daraei, 2021), but anaerobic digestion is getting increasing interest for the possibility of coupling with the carbon capture process (Salomoni, 2011).

Optimal control strategies are fundamental in hybrid polygeneration systems, as revealed by several studies (Menon, 2013), but the proposed works mainly focus on the optimal management of the system coupled with the grid (Rossi, 2016). In (Rejeb, 2022) the authors proposed a hybrid polygeneration system based on PVT collectors, Organic Rankine Cycle (ORC), proton exchange membrane electrolyzer (PEM) and liquefied natural gas (LNG). The model was implemented in EES software and optimization was carried out by means of genetic algorithm, setting as objective function the cost and the overall exergy efficiency. Results shows that optimal values of 16.24% for the exergy efficiency and 4.48 $ for the cost rate are obtained, basing on the TOPSIS decision-making process.

1.1 Aim and Novelty

As investigated in the literature review, many works analyse hybrid polygeneration systems for both residential and industrial end use. Furthermore, optimization algorithm are used for the optimal management strategy of hybrid systems coupled to smart networks. This paper introduces some important novelties in the scientific framework discussed:

- An innovative layout of a polygeneration system based on gasification unit and anaerobic digester, which exploit biomasses and alkaline electrolyzer fed by photovoltaic to meet the energy demand of a hospital.
- A novel control strategy proposed to guarantee an optimal functioning of the technologies considered. In fact, the configuration investigated allows the technologies to operate dynamically with optimal efficiency.
- A dynamic model of renewable technologies producing a gaseous compound useful for several applications in polygeneration energy systems.

The system proposed and discussed is part of a greater work which will be introduced and discussed in the following sections.

2 SYSTEM LAYOUT

The layout of the polygeneration system proposed in this work is shown in Figure 1.

This work is included in a wider project of a hybrid polygeneration system providing power, heating, cooling, hydrogen, oxygen, syngas, and biogas for several applications. The original project consists in a polygeneration system whose aim is to meet all the energy demands of the botanical garden José Celestino Mutis in Bogotá (Colombia). The internal combustion engine (ICE) and the photovoltaic (PV) systems are the technologies already available to meet the power demand. Moreover, the PV surpluses are used to feed an alkaline electrolyzer (AEC) which provides hydrogen that can be used to increase the LHV of the fuel injected into the ICE. Furthermore, oxygen produced by the AEC is exploited as a gasifying agent for a gasification unit which provides syngas to feed the ICE. Together with these technologies available, a solar thermal collectors (STC) field is used to meet the thermal energy demand of the system, together with the ICE used in cogeneration mode (CHP). The STC is also used to meet the thermal energy demand of an anaerobic digester which provides biogas which is used to feed the ICE too. As a first application of the control strategy, the energy demand of a hospital, already available from a previous work of the authors, is considered. The part of the layout which is of interest for this paper includes the PV system, the alkaline electrolyzer, the gasification unit, and the anaerobic digester (AD), equipped with the tanks for the storage of the gases. These gaseous flow rates are then mixed according to a precise control strategy to meet the fuel demand of the ICE used for cogeneration (CHP) purpose. The flow chart of the control strategy applied is proposed in Figure 2.

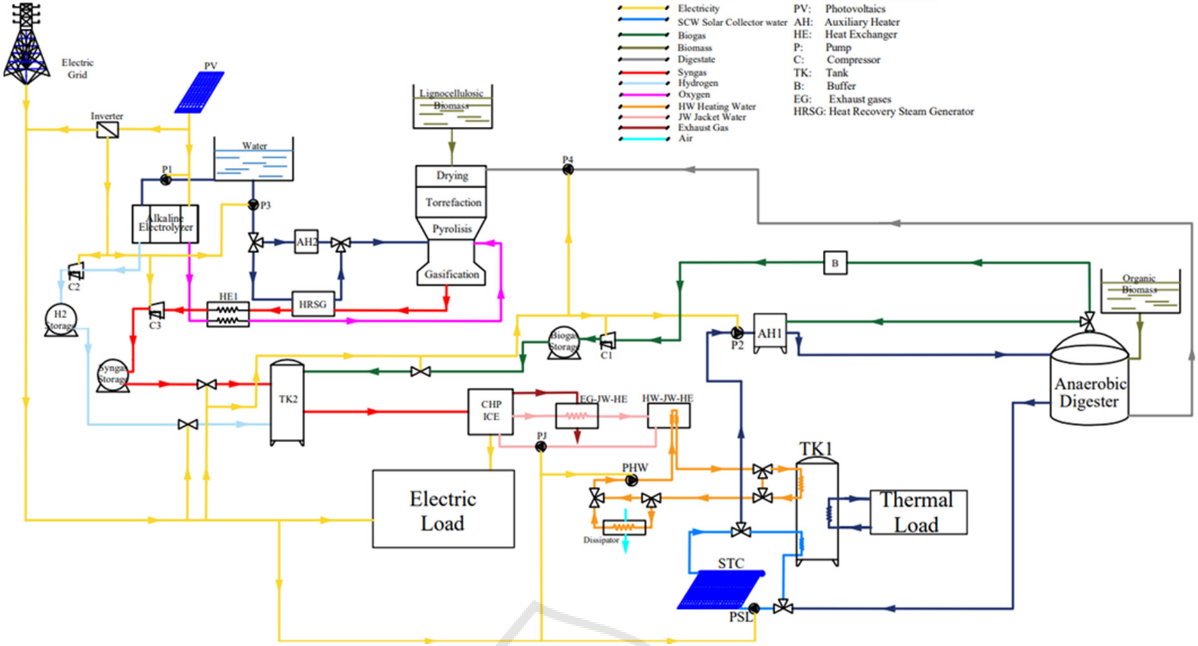

Figure 1: Layout of the system.

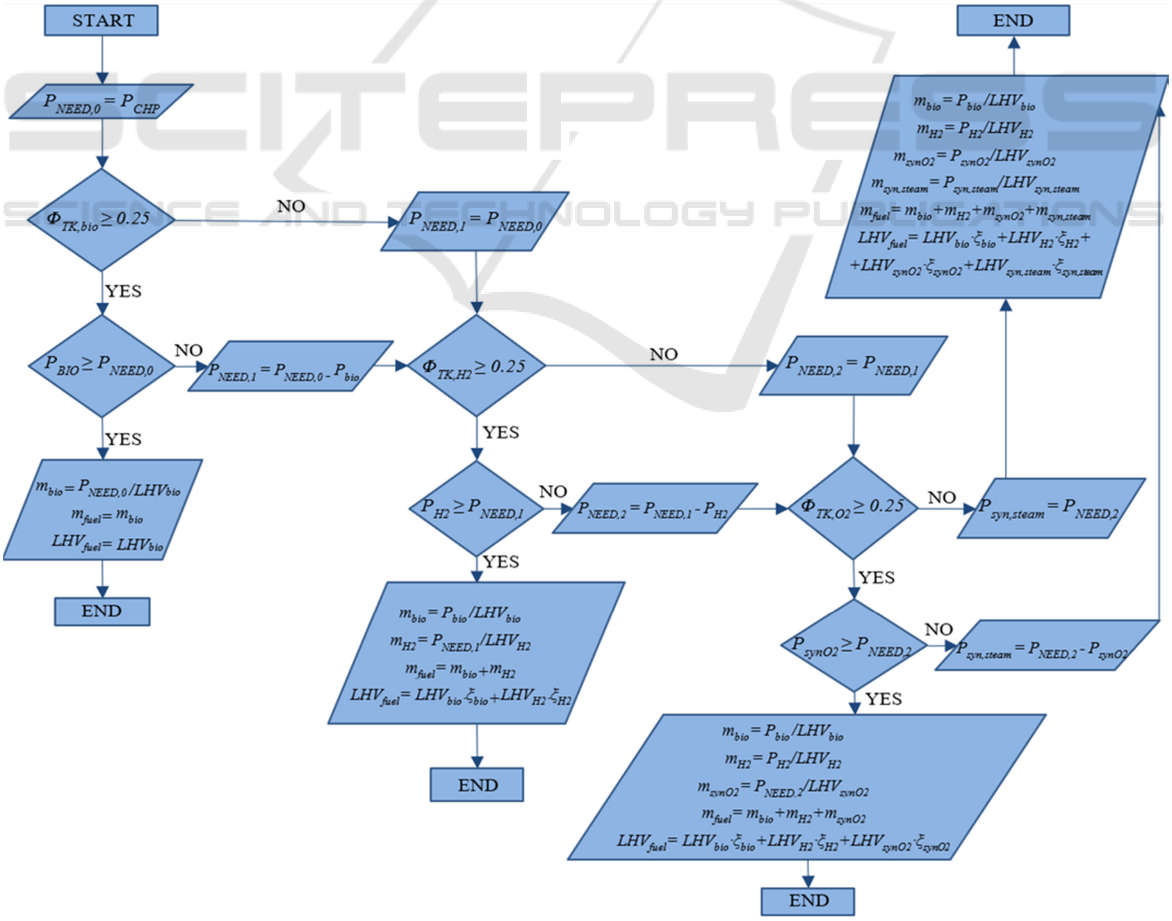

Figure 2: Flow chart of the control strategy.

As can be noticed from the flow chart, the backup technology which provides fuel to the CHP is the gasifier operating with steam as gasifying agent. In fact, when no power is available from the tanks, meaning that none of them is at least 25%, the gasifier gets immediately activated. In case the biogas tank is at least 25% full - $\Phi_{TK,bio} = 0.25$ - the fuel power available from biogas is the first one sent to the engine. The main reason for the adoption of this strategy is the constant flow rate of the biogas produced, which allows one to stabilize the fuel properties and increase the engine efficiency (Jatana, 2014) more easily.

To increase the LHV of the fuel and fully exploit the electrolyzer production, the hydrogen flow rate is immediately considered after biogas. More specifically, if the biogas flow rate is enough to meet the fuel demand, no more power is required from the system. If no biogas is available or the energy is not sufficient, the hydrogen tank is checked. At this point, if the pressure level of the H_2 tank is more than 25%- $\Phi_{TK,H2} \geq 0.25$ – the hydrogen flow rate is exploited, otherwise the gasification unit is exploited.

According to the same strategy, if it is possible to use oxygen as gasifying agent, it is used, otherwise the system exploits steam pre-heated with the outgoing syngas flow rate. In this case, there are two reasons to adopt this strategy. On the one hand, the oxygen produced is supposed not to be sold to the hospital, since it should undergo several purification steps to be usefully exploited.

On the other hand, the exergy efficiency of the gasification unit increases when using O_2 instead of steam as gasifying agent, and the biomass consumption is reduced (Kalıncı and Dincer, 2018). Thus, O_2 is used as gasifying agent as long as it is available, according to the pressure level in the tank. If the power generated is not enough or none of the tanks has sufficient charge, the steam flow rate is needed to feed the gasifier. The final lower heating value (LHV) of the fuel is calculated as the sum of the LHV of each component of the mixture times the fraction of the gas in the compound (ξ).

3 MODEL

The proposed layout integrates several technologies whose models were developed in large part by the authors. Some of these models are developed in EES software, as the gasifier (Barco-Burgos, 2021), others are developed in MatLab, as for the case of the alkaline electrolyzer (Firtina-Ertis, 2022). All the models are then integrated in the TRNSYS platform for dynamic simulation purpose (Calise, 2017).

For the sake of brevity, in this section only the main models are concisely discussed, namely:

- Gasifier
- Alkaline electrolyzer
- Anaerobic Digester

All the models are based on the assumption of ideal gas behaviour.

3.1 Gasification Unit

This model is a semi-empirical model already developed and validated by the authors in (Barco-Burgos, 2021). It simulates a downstream allothermal gasification unit that produces syngas from lignocellulosic biomass.

The calculation procedure starts with the following input: the temperature of the gasifier, the biomass composition, the gasifying agent/biomass ratio, tar composition, and heat losses. All these data are empirically verified. With these values, the equilibrium constants K1 to K3 are calculated and then the Newton-Raphson method is adopted to solve the system of nonlinear equations:

$$K1 = \frac{(n_{CO2})(n_{H2})}{(n_{CO})(n_{H2O})} \tag{1}$$

$$K2 = \frac{(n_{CH4})(n_{TOT})}{(n_{H2})^2} \tag{2}$$

$$K3 = \frac{(n_{CO})(n_{H2})^3}{(n_{CH4})(n_{H2O})(n_{TOT})^2} \tag{3}$$

The value of the here mentioned equilibrium constants, as a function of the temperature, are obtained from the JANAF thermodynamic tables (Chase,1975).

3.2 Alkaline Electrolyzer

This model is a model developed by the authors which simulates the operating voltage of the cell at different current input. The model is validated by experimental data provided in ref. (Firtina-Ertis, 2022), using the same approach of the overvoltage calculations. First the reversible voltage of the cell is calculated. Then, the activation, concentration, and ohmic overvoltages are calculated as well. The nonlinear system of equation integrated in the model is the following:

$$V_{cell} = V_{rev} + V_{act} + V_{conc} + V_{ohm} \tag{4}$$

$$V_{rev}(T,p) = V_{rev}(T_0,p_0) + \frac{RT}{nF}\ln\left(\frac{p_{H2}p_{O2}^{1/2}}{p_{H2O}}\right) \tag{5}$$

$$V_{act} = \frac{RT}{\alpha_c nF}\ln\left(\frac{i}{i_{0,c}}\right) + \frac{RT}{\alpha_a nF}\ln\left(\frac{i}{i_{0,a}}\right) \tag{6}$$

$$V_{conc} = -\frac{RT}{nF}\ln\left(1-\frac{i}{i_L}\right) \tag{7}$$

$$V_{ohm} = \left(\mathrm{R}_{electrode} + R_{membr} + \mathrm{R}_{electrol}\right)\cdot i \tag{8}$$

The molar production of hydrogen and oxygen is calculated according to the stoichiometry of the electrolysis reaction. Given that, the massic flow rates are known.

3.3 Anaerobic Digester

The model of the anaerobic digestion adopted is the ADM1, mainly used for biomasses with low total solid content (Ashraf, 2022). Details of this model can be found in ref. (Calise, 2023).

The system of equations used for the calculation of the biogas production from the input biomass has the following structure:

$$\frac{dS_{liq,i}}{dt} = \frac{q_{in}\mathrm{S}_{\mathrm{in},i}}{V_{liq}} - \frac{q_{out}\mathrm{S}_{\mathrm{in},i}}{V_{liq}} + \sum_{j=1}^{10}\varphi_j\alpha_{i,j} \tag{9}$$

Where the term S,i represents the concentration of the species "i" in the substrate, q is the flow rate, and V is the volume occupied by the biomass in the digester, supposed to be constant for a continuously stirred tank reactor (CSTR). The term $\varphi_{i,j}$ is the kinetic term and $\alpha_{i,j}$ is the biochemical coefficient per each process "j". The first order Monod kinetics for the biochemical reactions are considered. Arrhenius kinetics are used for the dependence from the reactor temperature. An accurate thermal model is also developed to iteratively calculate the influence of the evolving temperature on the AD process (Calise, 2023).

For the gas storage, the ideal gas behaviour is supposed for the compression of the compounds in the tanks.

4 CASE STUDY

In this section, the main data regarding the technologies modelled for the dynamic simulation are provided. As already mentioned, this case study is part of a larger project involving more renewable technologies and end users. For this control strategy, in fact, only the electric energy demand of a large hospital complex was considered for the internal combustion engine operation. The interest is indeed on the analysis of the control strategy applied to the technologies in charge of feeding the engine. More specifically, the engine is a JMS-612-GS-N.L.Jenbacher CHP engine of 2 MW of rated electric power, whose details are shown in Table 1. In this table, the most important data regarding the 2 MW alkaline electrolyzer (AEC) and the 1.7 MW gasification unit (GAS) are shown. The biogas flow rate is constant tanks to the use of a buffer downstream the digester, the volumetric flow rate is equal to 83.97 Nm^3/h.

The data regarding the hospital load and the CHP are provided with detail in (Cappiello and Erhart 2021). The hospital complex consists of several buildings, the total heated volume is 214´000 m^3 and the floor heated area is 18´640 m^2.

As will be discussed in the "Results" section, the power demand of the complex is quite stable over the year because of the intensive usage of electrical devices and hospital machineries (Cappiello and Erhart 2021).

5 RESULTS

This section shows and discusses the main results obtained from the dynamic simulation of the hybrid polygeneration system with the control strategy applied for the tanks.

Figure 3 (left) shows the power flow rates for the different gases considered. The results are perfectly consistent with the expected behaviour of the system. In fact, the energy provided by the biogas flow rate is constant and represent the baseload sent to the CHP during its operation. Only in the first moments of the

Table 1: Data of the main components.

Component	Parameter	Description	Value	Unit
CHP	-	Model name	JMS-612-GS-N.L	-
	-	Manufacturer	GE Jenbacher GmbH & Co OHG	-
	$P_{el,CH}P$	Rated power	2002	kW
	$P_{th,fuel}$	Rated fuel input	4424	kW
	$\eta_{el,CHP}$	Rated electric efficiency	0.452	-
AEC	N_{cell}	Number of cells in series	49	-
	N_{stack}	Number of parallel stacks	100	-
	$P_{el,AEC}$	Rated electrolyzer power	2200	kW
	T	Operating temperature	333	K
	p	Operating pressure	8	bar
GAS	$P_{th,GAS}$	Rated input power	1730	kW
	$m_{biomass}$	Rated biomass input	386	kg/h
	T_{agent}	Gasifying agent inlet temperature	700	K
	$T_{gasifier}$	Gasfication temperature	1123	K
	H_2O/bio	Steam/biomass ratio	0.85	-
	O_2/bio	Oxygen/biomass ratio	0.26	-

Table 2: Energy usage ratio.

R_{BIOGAS}	R_{H2}	$R_{SYN,O2}$	$R_{SYN,STEAM}$
0.15	0.03	0.45	0.37

day, when the biogas tank is less than 25% filled, the energy is entirely provided from the gasification unit. In this case, since no solar radiation is still available, the H_2 and O_2 tanks are not fed by the electrolyzer, then the steam is used as gasifying agent, see Figure 3 (right). In the first hours of the morning the biogas tank continuously sends fuel to the CHP but the energy mismatch is always met by the syngas produced with the steam. The reason is that the H_2 and O_2 tanks are still charging up to the desired state of charge, 25%.

Around 11 AM., the O_2 tank has reached enough charge to allow the oxygen to feed the gasifier. In this case, the syngas provided by the gasification unit has a higher LHV than the one produced with steam, and the effect is immediately beneficial. In fact, the higher the LHV of the syngas, the higher is the LHV of the mixture sent to the engine, Figure 4 (left). Moreover, the higher the LHV, the lower is the mass flow rate of fuel that is necessary to send to the CHP, Figure 4 (right).

The effect of the H_2 flow rate is the most relevant, as expected, on the increasing of the LHV of the fuel. In fact, despite a small amount of H_2 is sent during the allowed activation hours of the tank, the LHV of the compound increases from 70 to roughly 75 MJ/kg, see figure 5. This means that the flexibility in the energy sent to the ICE from the several tanks would be easily increased by simply applying a different strategy.

For the sake of completeness, Table 2 shows the values of the ratio of the energy share from the three different fuels during the year of functioning. As it is possible to observe, with this strategy the larger fraction, 0.45, is due to the syngas obtained from O_2, which is the first target for the control developed. Large share is also due to the syngas operating with steam, which means that the H_2 could be exploited more to increase the flexibility of the gaseous moisture.

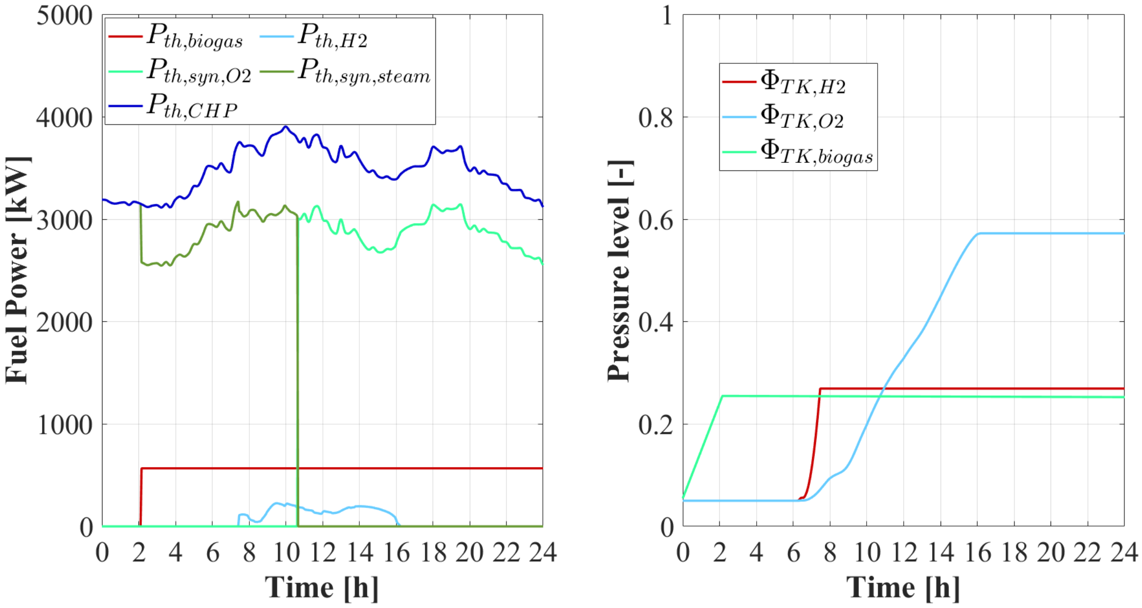

Figure 3: Fuel energy provided by the unit (left) and tank pressure level (right).

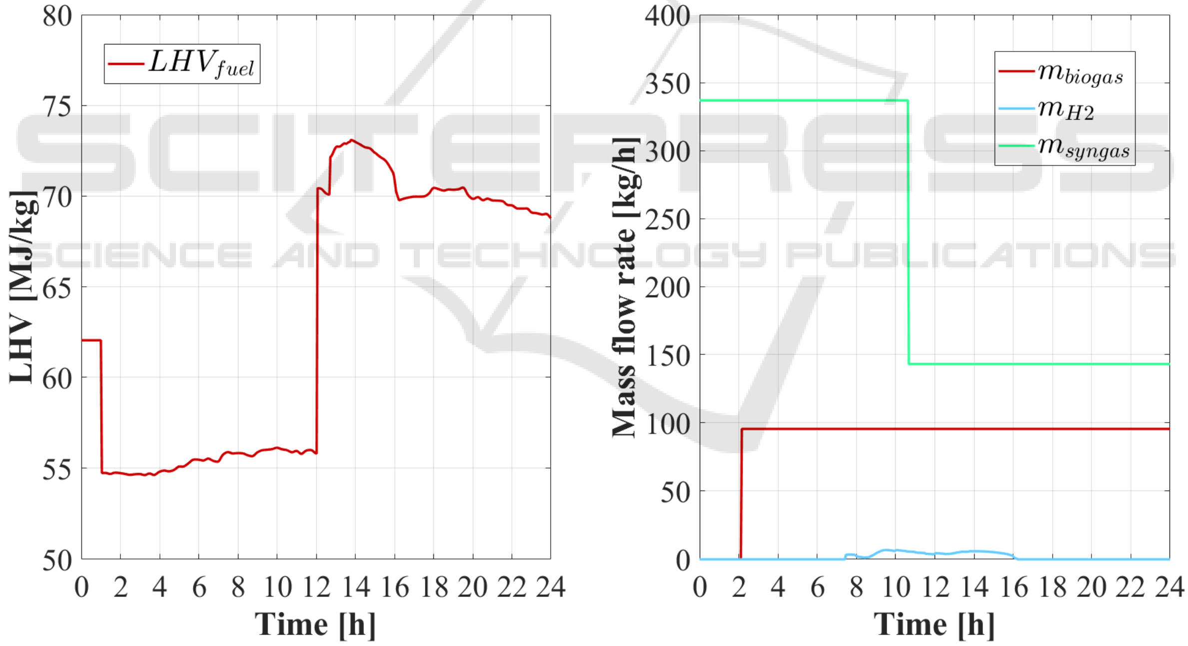

Figure 4: LHV of the fuel (left) and mass flow rate injected (right).

6 CONCLUSIONS

In conclusion, the control strategy proposed allows one to easily manage the several fuels available to exploit the technologies in the most convenient way, according to the different targets that could be set for the hybrid polygeneration system. In this case study the hospital complex had an almost constant energy demand and the first aim was to let the gasifier operate with oxygen as gasifying agent. In a different scenario, the first aim could be producing oxygen to be purified and used by the hospital complex and the system could be easily managed changing the control strategy.

The final aim of this work was to provide a suitable control strategy for the optimal dynamic operating conditions of a polygeneration system based on biofuels production which could be use for whatever application.

NOMENCLATURE

AD	anaerobic digestion
AEC	alkaline electrolyzer
CHP	cogeneration of heat and power
CPVT	concentrating photovoltaic-thermal
CSTR	continuously stirred tank reactor
GAS	gasification unit
ICE	internal combustion engine
LHV	lower heating value [MJ/kg]
LNG	liquefied natural gas
M	maintenance [euro/year]
m	mass flow rate [kg/h]
P	power [kJ/h or kW]
PEM	proton exchange membrane
PV	photovoltaic
PVT	photovoltaic-thermal
STC	solar thermal collectors
T	temperature [°C]
Subscript	
bio	biogas
fuel	fuel
H2	hydrogen
Need	demand
O2	oxygen
Steam	steam
Syn	syngas
TK	tank
Greek symbol	
η	efficiency [-]
ξ	gas fraction [-]
Φ	fill factor [-]

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