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Dynamic Simulation and Thermoeconomic Analysis of a Novel Hybrid Solar System for Biomethane Production by the Organic Fraction of Municipal Wastes

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Abstract: The anaerobic digestion of the organic fraction of municipal solid waste and the biogas production obtained from its stabilization are becoming an increasingly attractive solution, due to their beneficial effects on the environment. In this way, the waste is considered a resource allowing a reduction in the quantity of it going to landfills and the derived greenhouse gas emissions. Simultaneously, the upgrading process of biogas into biomethane can address the issues dealing with decarbonization of the transport. In this work, the production of biogas obtained from the organic fraction of municipal solid wastes in a plug flow reactor is analyzed. In order to steer the chemical reactions, the temperature of the process must be kept under control. A new simulation model, implemented in the MatLab® environment, is developed to predict the temperature field within the reactor, in order to assess how the temperature affects the growth and the decay of the main microbial species. A thermal model, based on two equilibrium equations, is implemented to describe the heat transfer between the digester and the environment and between the digester and the internal heat exchanger. A biological model, based on suitable differential equations, is also included for the calculation of the biological processes occurring in the reactor. The proposed anaerobic digestion model is derived by the combination of these two models, and it is able to simultaneously simulate both thermal and biological processes occurring within the reactor. In addition to the thermal energy demand, the plant requires huge amounts of electricity due to the presence of a biogas upgrading process, converting biogas into biomethane. Therefore, the in-house developed model is integrated into a TRNSYS environment, to perform a yearly dynamic simulation of the reactor in combination with other renewable technologies. In the developed system layout, the thermal energy required to control the temperature of the reactor is matched by a solar thermal source. The electrical demand is met by the means of a photovoltaic field. In this work, a detailed thermoeconomic analysis is also proposed to compare the environmental impact and economic feasibility of a biomethane production plant based on a plug flow reactor and fed by renewables. Several economic incentives are considered and compared to determine the optimal solution, both in terms of energy and economic savings. The plant is designed for the treatment of a waste flow rate equal to 626.4 kg/h, and the biomethane produced, approximately 850 tons/years, is injected into the national gas grid or supplied to gas stations. In the proposed plant, a solar field of an evacuated tube collector having a surface of approximately 200 m^2 is able to satisfy 35% of the thermal energy demand while over 50% of the electric demand is met with a photovoltaic field of 400 m^2. A promising payback time of approximately 5 years was estimated.

Keywords: organic fraction of municipal solid wastes; anaerobic digestion; dynamic analysis; biomethane; photovoltaic system; solar thermal collector

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1. Introduction

The correct management of waste and the use of renewable energy sources are crucial issues which are increasingly influencing the focus of the agenda of policy makers of the European Union [1]. The continuous increase in waste production, the contribution to global warming and the climate changes associated to their confinement in landfills have led to the development of efficient waste to energy technologies (WtE) to improve the energy recovery from the waste [2]. To face the ever-increasing issue of energy consumption and related environmental impact caused by all the energy sectors, the European Union (EU) issued several step-by-step directives aiming to achieve a full decarbonization by 2050 [3]. In this path, the Renewable Energy Directive—Directive (EU) 2018/2001, RED II—established a common framework for the promotion of energy from renewable sources in the EU and set a binding target of 32% for the overall share of energy from renewable sources in the EU's gross final consumption of energy by 2030 [4]. As a further step, the "fit for 55" package of the Directive issued in 2021 established that an overall reduction by 55% of Greenhouse Gases (GHG) compared to 1990 should be reached by the end of 2030 [5]. To this scope, several innovations in terms of energy taxation, energy trading systems and carbon border adjustment mechanisms were introduced [6]. More specifically, the necessity of decarbonizing the road transport sector was highlighted both in the RED II and the "fit for 55", pointing out that the integration of alternative fuels refueling stations are currently mandatory to meet the energy goals [7]. In particular, a recent EU Concilium established that by 2035, all the new registered road vehicles should be emissions-free [8].

To this scope, electric vehicles cannot be considered as the unique solution to fully decarbonize the road transport sector since the amount of electricity required to meet the vehicles' demand could not be provided only by renewables [9]. Furthermore, the necessity of adequate infrastructures to renovate the energy transmission and distribution through the current electric grid represents a relevant issue [10]. Moreover, these issues are even enhanced when considering hydrogen vehicles, since the hydrogen production and distribution infrastructure still only exist at a prototypal level [11]. Thus the usage of fuel cell vehicles is still premature for the near term future [12]. In particular, the production of biofuels for the biomethane from anaerobic digestion and a biogas upgrading process, is getting more and more appealing [13]. The most interesting aspect is that biofuels can be produced by the means of several types of biomasses [14]. On the one hand, this allows one to exploit a renewable energy source that is programmable, different from the solar and wind sources which are unpredictable [14]. On the other hand, the role of bioenergy is important for achieving renewable energy targets, in synergy with the concept of a circular economy [15]. Moreover, the production of biomethane, and biofuels in general, allows the countries to reduce their energy dependence and reduce the energy costs, as recently happened due to the war in Ukraine [16]. A worldwide urgent action is necessary which aims for the recovery and valorization of waste and biomass, in order to produce valuable materials and energy [17].

In this framework, the anaerobic digestion (AD) of the organic fraction of the municipal solid waste (OFMSW) plays a pivotal role, and it is a good opportunity in regards to both the need for waste disposal and the production of energy by renewable sources [18]. The work of Ampese et al. [19] proves that the AD process represents a hot topic focus of the scientific research, and that the use of renewable fuels becomes, increasingly, a worldwide trend.

Anaerobic digestion is a process by which almost any organic waste can be biologically converted into another species, due to a series of metabolic reactions such as hydrolysis, acidogenesis, acetogenesis and methanogenesis [20]. The conversion takes place thanks to different microbial species in anoxic conditions [21]. AD occurs in suitable reactors, and Mahmudul et al. report a review on the pros and cons of them [22]. Continuous stirred-tank reactors (CSTRs, which use mechanical agitation or effluent) and plug flow reactors (PFR, where the reactor content is propelled along a horizontal reactor) are able to better control the biological conditions due to the variability of the OFMSW characteristics [23] and are more commonly used for biogas production [24]. PFRs exhibit several advantages in comparison to CSTRs, such as an appropriate use of the working volume, higher capacity for overloads, more protection against acidification and the generation of concentration profiles along the reactor [25]. The kinetics of biogas production is high due to a plurality of factors: high concentration of organic matter in the initial sections of the reactor, the near absence of fermentable matter and a low concentration of microorganisms at the end of the process [26]. On the other hand, PFRs may undergo instabilities due, for example, to the cascading acidification that results from the low local retention time of each section of the reactor [25].

The final products are the digestate and biogas, which can be used for energy purposes [27]. The digestate represents the solid residual, rich in readily available macro- and micro-nutrients which can be used in agriculture as biofertilizer [28]. The biogas is a mixture of gases that mainly includes methane (CH_4) and carbon dioxide (CO_2), with small amounts of hydrogen (H_2), nitrogen (N_2), hydrogen sulphide (H_2S), oxygen (O_2), water (H_2O) and saturated hydrocarbons (i.e., ethane and propane) [29]. Biogas can be utilized to generate electricity and heat separately, or for combined heat and power (CHP) generation [30]. If biogas is purified and upgraded to biomethane, it can be fed into the natural gas grid and/or used as fuel for vehicles [31]. The first process is a cleaning aimed to remove the harmful and toxic compounds [32], such as H_2S. Conversely, the upgrading process aims at decreasing CO_2 content, simultaneously increasing the heating value of the biogas [33]. More than 1000 biomethane plants were operating worldwide during 2020 [34]. In Europe, more and more biomethane plants have been installed in the past few years: numbering from 187 plants in 2011 up to a total of 729 plants in 2020. Germany presents the highest number of biomethane plants, followed by the UK and Sweden. Pressure swing absorption (PSA), water, organic solvent, chemical scrubbing and separation employed through membrane and cryogens are a few of the commercially available biogas purification systems [35]. They are widely employed, accounting for 98% of all upgrading facilities. A common factor of all these techniques is that the removed CO_2 is normally released back into the atmosphere [36]. The membrane separation process is particularly appealing for biogas upgrading, due to its moderate energy consumption, good selectivity, easily engineered modules and therefore lower costs. High CH_4 recovery efficiency can be reached (>96%), while pure CO_2 can be obtained. The main disadvantage of the membrane separation process is that multiple steps are required to reach high purity [37]. Since the commercially applied technologies for biogas upgrading are energy-intensive [38], researchers' efforts moved toward the study of new technologies. Starr et al. analyzed alkaline with regeneration (AwR) and bottom ash upgrading (BABIU), which not only selectively remove CO_2 from the biogas but they also store it [36]. However, data for these novel technologies is actually based on laboratory values and, therefore, they need further investigations. A direct hydrogen injection [39] and additives [40] are alternatives in situ biogas upgrading technologies. However, the first one needs a significant improvement to reduce the energy used for H_2 gas-to-liquid transfer in order to be economically feasible, [41] while the second one affects the post-treatment of digestate [42].

The biogas production and Its composition do not depend only on OFMSW [43] characteristics, but also on process conditions (batch or continuous; wet or dry; mesophilic or thermophilic fermentation) [44]. Temperature is one of the main factors affecting the anaerobic digestion [45]; it significantly affects the activity of the main microbial species [46] responsible for the biogas production, and it is necessary that the reactor is equipped with a heating system to control its temperature. The anaerobic digestion process can take place under mesophilic conditions with an operating temperature ranging from 35 °C to 40 °C and from 50 °C to 60 °C under thermophilic conditions [47]. Because mesophilic digestion operates at a lower temperature, digestion at this temperature regime is slower and yields a lower amount of biogas. However, mesophilic digesters remain attractive because of their lower heating costs compared with thermophilic digesters [48]. Therefore, biological and thermal models have to be implemented to describe the anaerobic digestion process. The biological model is used to predict the amount of biogas produced by chemical reactions, which are simulated considering their specific operating temperature. A detailed thermal model is also required to simulate the digester thermal behavior and predict the heat transfer between the digester and the water heat exchanger or the environment [49].

A biogas plant requires thermal energy to supply the digester and to keep its temperature within the designed operating range. It requires electric energy to activate some equipment, as pumps and mechanical stirring add to the biogas upgrading process. Once again, in the framework of the above-mentioned EU goals, the biogas plant can be integrated with renewables to avoid or reduce the use of natural gas and electric power from the grid. In particular, solar technologies (solar thermal collectors, photovoltaic panels or photovoltaic/thermal collectors) can be easily integrated in these plants [50]. A new conception of a solar anaerobic digestion unit was proposed by Ouhammoun et al. [51]. The plant consists of an Upflow Anaerobic Sludge Blanket (UASB) digester coupled with a flat plate collector (FPC). Two storage tanks are also included to cover the heat demand of the digester when the solar irradiance is not available. To analyze its performance, a modelling simulation was developed and implemented in a TRNSYS platform, and the results showed that the current system can achieve 100% energy autonomy. Lombardi et al. investigated the possibility to integrate thermal solar collectors into a plant, including a CSTR and an upgrading unit [52]. The supplied solar thermal energy allows one to save a certain amount of biogas used for heating the reactor, enhancing the production of biomethane. The thermal and economic analyses were performed using different collector types and for different geographical locations. They observed that economic acceptability can be reached only using the less expensive collector, even if its efficiency determines lower biomethane savings. In the work of Gaballah et al. [53], experiments on a household digester have been conducted aiming to investigate the potential of integrated solar heating techniques to increment its performance in China's cold regions. Two cases have been analyzed. The first one consists in a digester equipped with a solar greenhouse, while the second case provides the addiction of a solar water heating system and a heat exchanger under the digester. The results have shown that using an integrate solar energy allows an increase in the slurry temperature, but no significant variation in the biomethane production. Mahmudul at al. provided a review of the most recent studies from the relevant academic literature on waste to energy technology (particularly AD technology) for biogas production, and the application of a solar-assisted biodigester (SAB) system [54]. In this system, solar energy is collected from sunlight using the collector and converted into electricity using a battery and DC-AC converter, which provide the appropriate temperature for converting the waste into energy. The study revealed that the solar-assisted AD system produces less pollution and exhibits a better performance, compared with the conventional AD system. Li et al. showed theoretical and experimental results of a solar temperature-controlled biogas production system [55]. The plant was developed in Lanzhou City, China, mainly consisting of an insulated anaerobic reactor and a solar collector with 30 sticks of $\Phi58 \times$ L1800 mm evacuated tubes. Their work represents a scientific basis and engineering reference for the application of biogas production that is temperature-controlled by solar energy, and has important value for the efficient and low-cost anaerobic digestion treatment of agricultural and animal husbandry wastes in cold and arid areas. Conversely, Khalid et al. [56] and successively Zaied et al. [57] used a photovoltaic system to warm up the palm oil mill effluent and cattle manure mixture, in order to maintain the required reactor temperature. The proposed biogas plant seems to be economically feasible; a payback period of approximately 5 years may be achieved if this technology is used on a large scale. The biogas plant electric demand is due to its own equipment operation, such as pumps and mixers, and is mainly due to the upgrading technologies. A rooftop photovoltaic system is used to supply the electric energy demand of an integrated AD-composting plant operating in South Italy, and described in the work of La Pera et al. [58]. It covers an area of approximately 12,000 m^2 with electricity production, for plant activities relative to the year 2020 of approximately 3 MW. Aiming at achieving a more sustainable and efficient biomethane production, Tian et al. proposed a novel system, which integrates concentrating a photovoltaic/thermal hybrid (C-PV/T) in the upgrading biogas [59]. Due to the ability to produce electricity and heat simultaneously and efficiently, C-PV/T can provide the demand of both the electricity and heat required by the regeneration of the solvent in the chemical absorption upgrading process. Without the storage of energy, C-PV/T could only provide 17% of the heat demand and 51.1% of the electricity demand during the process. At the same time, Hao et al. presented a hybrid digestion system, integrated with a concentrated photovoltaic/thermal (C-PV/T) system for biogas production [60]. In this case, the results show that approximately 7% of the heat consumption and 12% of the electricity consumption of the biogas plant can be covered by solar energy, by using the produced heat in a cascading way according to the operating temperature of different processes. Biogas yield is expected to be increased by 1.7% with such systems, and the payback period is approximately 10 years. Experimental studies on the contribution of solar energy for the heating of an anaerobic digestor have been conducted by Darwesh et al. [61]. In particular, the required mesophilic conditions have been satisfied, integrating an evacuated tube solar collector with an auxiliary electrical heater placed inside the storage tank. The latter was necessary to provide for the unavailability of solar energy during the night and at different times. The solar energy system was able to cover approximately 75% of the energy demand of the reactor, considering an operational temperature of 37 °C. The cost analysis showed that the project has good economic feasibility with a payback period of 1.7 years. Mehrpooya et al. presented a study on an integrated process of cryogenic biogas upgrading, by using renewable energy resources for sustainable development [62]. A parabolic trough solar collector (PTC), organic Rankine cycle (ORC) power system and absorption refrigeration cycle are used in this process to separate the impurity of raw biogas. The PTC supplies the required heat for the ORC and absorption refrigeration cycles. The results show that an integration upgrading process allows one to obtain an acceptable biogas purification and an overall exergy efficiency of 71.6%. In another study, Mehrpooya et al. designed a solar-driven water scrubbing process, integrated with flat plate solar collectors and a Kalina power cycle [63]. The power required for the compressor and pumps was provided by the Kalina cycle, recovering solar thermal energy and the heat of biogas compression. An auxiliary heater was employed to provide heat in case of scarce/null solar radiation. The water scrubbing process is capable of removing the CO_2 and H_2S contents, and the exergy efficiency of the proposed integrated system is found to be 92.36%. A life cycle energy and cost analysis of biogas plants integrated with solar PV systems has been conducted by Ali et al. [64]. They have collected data from 20 small scale plants and 20 PV systems from 3 different sub-districts of Bangladesh. The study suggests that the higher the plant size, the higher the efficiency in terms of produced biogas, but also the higher the installation costs. In work by Cappiello et al. [65], a comparison between two biogas upgrading technologies coupled with photovoltaic panels and an electric energy storage system was proposed. A photovoltaic field of 200 kW and a lithium-ion battery of 182 kWh allow one to achieve an almost grid-independent plant, producing enough electricity to be able to meet approximately 92% of the plant demand. Su et al., developed a mathematical model to simulate a hybrid system, including concentrated photovoltaic thermal (C-PV/T) collectors and biogas upgrading technology [66]. The thermal energy of the solar collectors is used for heating the digester unit, whereas the electric energy is used to supply the biogas upgrading unit to produce biomethane. The proposed configuration allows the reduction in the amount of electricity withdrawn from the grid by 48.38%, increasing biomethane production by 86.08%.

On the basis of the previous literature review, the anaerobic digestion process and the mathematical models aiming to describe the biochemical and biological aspects occurring during the waste stabilization are well known and consolidated. However, the works that describe the thermal aspects of the process and their influence on the biological aspects are yet few. Moreover, knowing the fundamental role of the anaerobic digestion process in the aim of a more aware waste management and biogas production, the attention of the current scientific research is focused on making the process more and more self-sufficient and independent by the use of natural gas and electric power from the grid. Hence the need to have a simulation model to analyze a so-made integrated system. It is within this context that this work arises.

The authors have simulated the anaerobic digestion process through a new model that takes into account both the kinetics of reactions and the heat exchanges occurring inside the reactor. The last has been integrated with renewables to meet its energy demand. At the end, the whole plant has been implemented in a dynamic simulation tool to test the influence of the environmental condition variations on the system's performance. In particular, this work proposes a novel system layout for the biomethane production by the anaerobic digestion of OFMSW in a plug flow reactor, working under mesophilic conditions, combined with solar thermal collectors. An upgrading unit based on the membrane technology completes the biogas plant. It is coupled with an evacuated tube collector field and a photovoltaic field to match its energy demand.

In order to evaluate the energy efficiency and the economic feasibility of the investigated plant, the following advances with respect to the state of the art are included:

- A digester model able to describe the biological aspects of the digestion process and the thermal heat exchange was implemented;
- A dynamic simulation model was implemented in a TRNSYS environment to evaluate the time-dependent biogas flow rate, taking into account the variation of the ambient temperature. The upgrading unit was simulated by an in-house developed model, since this component is not available in TRNSYS;
- A thermoeconomic model was developed considering in detail the capital and operating costs of the overall plant and including, also, the public incentive acknowledged due to the biomethane produced and injected into the public gas grid.

2. System and Method

This work presents a dynamic analysis of a fully renewable plant for the production of biomethane from Organic Fraction of Municipal Solid Waste (OFMSW). The core of the plant is a Plug Flow Reactor (PFR), where the anaerobic digestion process occurs. It is designed to work with an input water temperature equal to 55 °C. In order to satisfy the thermal energy demand to control the operating temperature of the digester, the PRF is coupled to a field of evacuated tube solar thermal collectors. Moreover, a photovoltaic field supplies the electric power for the pumps and the upgrading process.

The dynamic simulations of the proposed system were performed in a TRNSYS environment (version 17), including a large library of mathematical models for different components ("Types"). A model to simulate the processes occurring within the PFR was integrated into it. This model was developed with MATLAB, and allows the prediction of the temperature gradient along the reactor and the biogas production from the organic waste. Finally, a thermoeconomic model for a global assessment of the proposed system is also presented.

2.1. Layout

The following Figure 1 shows the detailed layout of the proposed renewable energy system:

The thermal circuit is split into two parts by the thermal energy storage tank, decoupling the solar loop by the digester water loop. The solar loop is equipped with the pump P1 and a solar field of evacuated tube collectors (ETC). A heat exchanger (HE 1) is also used to prevent the tank from overheating. When the water temperature $T_{out,ETC}$ rises over 80 °C, a counterflow water at a lower temperature is supplied to HE 1 to dissipate the excess heat. If the tank bottom temperature is $T_{b,TANK} > T_{out,ETC}$ or the total radiation is $G < 10\text{W/m}^2$, the controller supplies a signal that switches the P1 off in order to prevent thermal energy dissipation, and the water is not sent to the collectors.

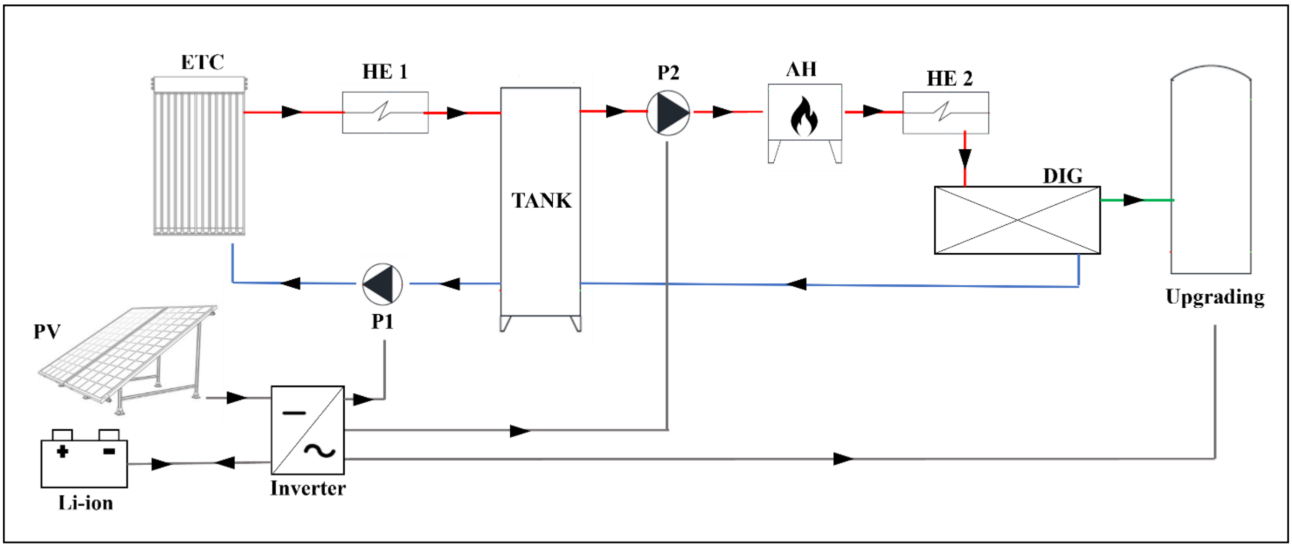


Figure 1. Layout of the plant.

Two main circuits are included in the plant: the thermal and the electricity circuits.

On the other side, the hot water is pumped by the constant speed pump P2 toward the auxiliary heater (AH). The set point temperature of the AH is fixed at 55 °C. If the fluid temperature is below the set point, the AH is turned on to heat the water of the cycle before entering the digester. The second heat exchanger (HE 2) at the outlet of the AH is designed to avoid the digester overheating. It rejects the heat to the environment when the water temperature exceeds the reactor operating temperature. The water exiting from the PFR is supplied to the tank, and the thermal circuit is closed.

The electricity circuit includes a photovoltaic (PV) field. An inverter is used to convert the direct current into an alternate current and to manage the maximum power point operation of the PV field. In addition, a lithium-ion battery storage (Lib) is used to limit the electricity exchanged with the grid.

2.2. Anaerobic Digester Model

The anaerobic digester model was described in detail in reference [49]. It consists of two models: the biological model and the thermal model. The biological model is based on the simplified version of the anaerobic digestion model n.1, the most commonly used mathematical model to describe the AD process [54]. The thermal model consists of two energy balance equations. The peculiarity of the developed simulation model is the integration of these two models, to simultaneously consider the thermal heat exchange between the waste and the internal heat exchanger and the thermal dissipations toward the environment, along with the temperature-dependent kinetics of the biological model.

The equations constituting the thermal model are the energy balance equation of the digester (Equation (1)) and the heat exchanger equation (Equation (2)).

$$\begin{aligned}\dot{m}_{water}c_{p,water}(T_{water,in} - T_{water,out}) + \dot{m}_{OFMSW}c_{p,OFMSW}T_{OFMSW,in} - \dot{m}_{digestate}c_{p,digestate}T_{digestate,out} \\ -\dot{m}_{biogas}c_{p,biogas}T_{digestate,out} - \dot{Q}_{dis} = \rho_{OFMSW}V_{OFMSW}c_{p,OFMSW}\frac{dT_{OFMSW}}{dt}\end{aligned} \quad (1)$$

$$\dot{m}_{water}c_{p,water}(T_{water,in} - T_{water,out}) = nU_{HE,n}A_{HE,n}(\overline{T_{water}} - \overline{T_{OFMSW}}) \quad (2)$$

The two variables are the output water temperature $T_{water,out}$ and the output digestate temperature $T_{digestate,out}$. The model takes into account the heat transfer between the

OFMSW and the internal heat exchanger in Equation (2) and the heat transfer between the reactor and the environment by the dissipative term $\dot{Q}_{dis}$ in Equation (1).

$$\dot{Q}_{dis} = U_{cover}A_{cover}\left(\overline{T_{OFMSW}} - T_{amb}\right) + U_{walls}A_{walls}\left(\overline{T_{OFMSW}} - T_{amb}\right) + U_{foundation}A_{foundation}\left(\overline{T_{OFMSW}} - T_{ground}\right) \quad (3)$$

The three terms of Equation (3) are the flow rate loss through the digester cover, lateral walls and basement, respectively. U_i are the global heat transfer coefficients, and the overlined terms represent the spatially averaged value.

The reactor and biogas temperatures are assumed to be equal to $T_{digestate,out}$. It is the most important parameter because it affects the AD process. $T_{digestate,out}$ dramatically affects the kinetics of the microbiological species responsible for the biogas production. Therefore, the thermal model is strictly linked to the biological model, and the $T_{digestate,out}$ is an input parameter for the latter.

The biological model consists of 13 differential mass balance equations, one for each organic matter component. Assuming that the volume occupied by the waste V_{OFMSW} remains constant, the generic equation can be written as follows:

$$\frac{dC_{OFMSW,i}}{dt} = \frac{\dot{V}_{OFMSW}}{V_{OFMSW}}\left(C_{OFMSW,i,in} - C_{OFMSW,i}\right) + \sum_j \rho_j \nu_{i,j} \quad (4)$$

C_{OFMSW} represents the concentration of the considered substate and is expressed in $\mathrm{kg}COD/\mathrm{m}^3$; ρ_j is the kinetic of reaction of the process and $\nu_{i,j}$ is the biological coefficient.

2.3. TRNSYS Model

The majority of the components used in this work were taken from the TRNSYS Library, whereas some other models were specifically developed for the scope of the work and based on manufacturers' data.

As mentioned in the previous section, it was necessary to develop a model for the simulation of the anaerobic digester, since this component was not available in the TRNSYS Library. The model was developed in Matlab, and it requires as input data the temperature and mass flow rate of water and OFMSW as reported in the following Table 1.

Table 1. The input parameters to the digester.

Parameter	Description	Unit
$T_{water,in}$	Inlet hot water temperature	°C
$T_{OFMSW,in}$	Inlet OFMSW temperature	°C
$\dot{m}_{water}$	Mass flow rate of the inlet hot water	kg/h
$\dot{m}_{OFMSW}$	Mass flow rate of OFMSW	kg/h

In particular, the inlet OFMSW temperature was assumed to be equal to the ambient temperature that is from weather data supplied by the "Type 109-TMY2" of the TRNSYS Library. As a result, in addition to the outlet cold water and digestate temperature, the biogas flow rate $\dot{m}_{biogas}$ and the thermal flow rate exchanged between water and waste are obtained.

The produced biogas is supplied to an upgrading process. This component is not available in the TRNSYS Library, and a suitable model was purposely developed. The model predicts the biomethane yield after the upgrading process. The upgrading unit consists of a 3-stages selective membrane system, equipped with 3 compressors [67]. In this membrane separation process, CO_2 is removed from the biogas mixture by means of a physical filtration through hollow fiber selective membranes [37]. The obtained biomethane was predicted on the basis of some specific simplifying assumptions:

- The percentage of methane CH_4 in the biogas is equal to 65%;
- The separation efficiency of the process $\eta_{upgrading}$ is constant and equal to 99.5%;
- The outlet biomethane has a purity percentage of 98%.

Given the biogas volumetric flow rate $\dot{V}_{biogas}$, the biomethane volumetric flow rate was calculated as follows:

$$\dot{V}_{bioCH_4} = \frac{\dot{V}_{biogas} \cdot \%CH_4 \cdot \eta_{upgrading}}{\%purity} \tag{5}$$

and the electric power requested by the upgrading process was equal to:

$$Pel,upgrading = 0.2VbioCH_4 \tag{6}$$

2.4. Thermoeconomic Model

To evaluate the energy efficiency and the economic feasibility of the investigated plant, the energy and economic model are presented. The proposed system is a new plant to realize completely from scratch. The produced biomethane is injected into the natural gas grid.

The Simple Pay Back (SPB) period was calculated to estimate the system profitability. It is equal to the ratio between the total investment INV_{tot} and the yearly costs C for the proposed system:

$$SPB = \frac{INV_{tot}}{C} \tag{7}$$

The capital costs of all the components of the plant are also calculated. The most expensive component is the digester, being its capital cost related to its volume V_{Dig}:

$$INV_{Dig} = 4800V_{Dig} \tag{8}$$

The capital cost of the evacuated solar collectors is assessed as a function of their active surface area A_{ETC}:

$$INV_{ETC} = 300A_{ETC} \tag{9}$$

The photovoltaic capital cost includes the cost for the panels and the cost for the battery:

$$INV_{PV} = 1000P_{p,PV} + 200C_{Lib} \tag{10}$$

where $P_{p,PV} = GA_{PV}\eta_{PV}$ is the peak power depending on the PV area A_{PV} and C_{Lib} is the battery capacity.

The cost of the tank, including all the safety equipment and thermal insulation, is referred to its volume V_{TANK} [68]:

$$INV_{TANK} = 494.9 + 808V_{TANK} \tag{11}$$

The cost of the pumps is expressed as a function of their nominal mass flow rate $\dot{m}_p$ [68]:

$$INV_p = 389 \ln\left(\frac{\dot{m}_p}{1000}\right) - 283.15 \tag{12}$$

According to the values available in Chen et al.'s work [37], the upgrading unit capital cost is calculated as follows:

$$INV_{upgreding} = 7300\dot{V}_{bioCH_4} \tag{13}$$

The operative costs are due to the energy and maintenance costs M assessed as approximately 1% of the total investment costs:

$$C = \frac{E_{ee,fromGrid}}{\eta_{ee}} Cu_{ee} + \frac{E_{th,AH}}{\eta_{AH} LVH_{wc}} Cu_{wc} + M - V_{bioCH_4} Cu_{GN,toGrid} \quad (14)$$

where $E_{ee,fromGrid}$ is the electric energy withdrawn from the grid, $E_{th,AH}$ is the thermal energy provided by the woodchip (wc) AH and V_{bioCH_4} is the volume of the biomethane exported to the grid.

The primary energy (PE) required by the proposed system is evaluated as follows:

$$PE = \frac{E_{ee,fromGrid}}{\eta_{ee}} \quad (15)$$

It is equal to the PE consumption due to the electric energy withdrawn from the grid. The PE consumption due to AH is null because a woodchip fire was considered.

For the evaluation of the CO_2, it is worth noting that all the energy/fuels produced by renewables (biomass and solar) do not produce any CO_2. In fact, no CO_2 is emitted by solar collectors. In regards to biomass, it has been assumed that the amount of CO_2 emitted during the energy utilization process is equal to the CO_2 used for the growth of the biomass. Therefore, for the considered plant, CO_2 is only produced for the electricity withdrawn from the grid and produced by conventional fossil fuels-based power plants and can be calculated through the following equation:

$$MCO_2 = E_{ee,fromGrid} e_{CO_2,ee} \quad (16)$$

The main parameters adopted in such equations are reported in Table 2.

Table 2. Parameters used in energy, environment and economic analyses.

Parameter	Description	Value	Unit
η_{ee}	Electric efficiency of national grid	0.46	-
η_{PV}	Electric efficiency of PV	0.156	-
η_{AH}	Thermal efficiency of AH	0.95	-
Cu_{ee}	Purchasing unit cost of electric energy	0.18	€/kWh
$C_{u,wc}$	Unit cost of woodchip	0.06	€/kg
$Cu_{GN,toGrid}$	Unit cost of natural gas	1.30	€/Sm^3
LHV_{wc}	Woodchip lower heating value	3.7	kWh/kg
LHV_{bioCH_4}	Biomethane lower heating value	9.59	kWh/Sm^3
$e_{CO_2,ee}$	Unit emission of CO_2 per kWh of electric energy consumed	0.48	$kgCO_2$/kWh

3. Case Study

The analyzed case study refers to a PFR designed for a 30-days hydraulic retention time (HRT) and a waste flow rate of 626.4 kg/h. The digester is equipped with a heat exchanger consisting of 10 high-density cross-linked polyethylene pipes operating in parallel flow. The plant operates 24/7 for 365 d/y.

The inlet parameters of the developed model are summarized in Table 3. The thermal and geometrical parameters of the digester and the heat exchanger are also reported. The last data represent the composition of the waste inlet in the reactor.

Table 3. Inlet parameters of the developed model.

Parameter	Description	Value	Unit
$\dot{m}_{OFMSW}$	Mass flow rate of OFMSW	0.174	kg/s
$\dot{m}_{water}$	Mass flow rate of hot water	0.686	
ρ_{OFMSW}	Density of OFMSW	750	kg/m^3
HRT	Hydraulic Retention Rate	30	d
$T_{in,water}$	Temperature of hot water	55	°C
$c_{p,OFMSW}$	Specific heat of OFMSW	2.72	kJ/kg K
$c_{p,digestate}$	Specific heat of digestate	4.18	
$c_{p,biogas}$	Specific heat of biogas	1.42	
$c_{p,water}$	Specific heat of water	4.18	
n	Number of high-density cross-linked polyethylene pipes	10	-
U_{cover}	U-value of digester cover	3.6	W/m^2 K
U_{wall}	U-value of digester later walls	3.45×10^{-1}	
$U_{foundation}$	U-value of foundation of digester	3.06×10^{-1}	
$U_{HE,n}$	U-value of n^{th} pipe of Heat Exchanger	220	
A_{cover}	Exchange area of digester cover	175	m^2
A_{wall}	Exchange lateral area of digester	120	
$A_{foundation}$	Exchange area of foundation of digester	150	
$A_{HE,n}$	Exchange area of n^{th} pipe of Heat Exchanger	1.2	
X_C	Concentration of the complex organic substance	300	kgCOD/m^3
X_{acid}	Concentration of the acidogenic bacteria	0.001	
X_{metaAC}	Concentration of the acetoclastic methanogens bacteria	0.001	
X_{metaH_2}	Concentration of the hydrogenotrophic methanogens bacteria	0.001	

Assuming an ETC efficiency η_{ETC} equal to 53%, the area of the ETC was calculated by the following equation:

$$A_{tot,ETC} = \frac{\dot{Q}_{reactor}}{G \cdot \eta_{ETC}} \tag{17}$$

where $G = 1000 \mathrm{W/m^2}$ is the beam radiation and $\dot{Q}_{reactor}$ is the thermal flow rate that must be supplied to the reactor. The latter was calculated as the sum of the thermal loss $\dot{Q}_{diss}$ and the heat transfer rate supplied to the OFMSW:

$$\dot{Q}_{OFMSW} = \dot{m}_{OFMSW} c_{p,OFMSW} (T_{reactor} - T_{OFMSW,in}) \tag{18}$$

In Equation (18), $c_{p,OFMSW}$ is the waste specific heat, $T_{reactor}$ is the reactor operating temperature assumed to be equal to 40 °C and $T_{OFMSW,in}$ is the inlet waste temperature assumed to be equal to the ambient temperature in the most severe conditions.

The rated flow rate of the pump P1 was assessed as a function of the ETC area, considering a specific pump volume $v_{P1} = 25 \mathrm{l/m^2}$:

$$\dot{m}_{P1} = \nu_{P1} A_{ETC} \tag{19}$$

Otherwise, the rated flow rate of the pump P2 $\dot{m}_{P2}$ was assumed to be equal to the water flow rate inlet of the reactor $\dot{m}_{water}$ necessary to satisfy the thermal energy demand of the digester. Assuming a water temperature difference of 10 °C between the inlet and outlet of the reactor, it was calculated with the following equation:

$$\dot{Q}_{reactor} = \dot{m}_{water} c_{p,water} \Delta T \tag{20}$$

where $c_{p,water} = 4.18 \frac{kJ}{kg°C}$ is the water specific heat.

The tank is a thermal reservoir, modelled as a multi-layer system where each layer is perfectly mixed and having the same thickness equal to 0.5 m. Its volume depends on the ETC total area and on the ETC specific volume v_{ETC}:

$$V_{TANK} = \frac{v_{ETC} A_{tot,ETC}}{1000} \tag{21}$$

with $v_{ETC} = 50 \text{ L/m}^2$.

The PV field extension is evaluated using the same approach but considering an efficiency $\eta_{PV} = 15.6\%$. However, in this case, the selection of PV capacity also depends on the selection of the capacity of the battery storage. A lithium-ion battery of 250 kWh was chosen.

4. Results and Discussion

As mentioned before, the dynamic simulation of the system was implemented in a TRNSYS simulation environment over a period of one year. In this section, the results are shown and discussed. A comprehensive overview of the system performance is provided, including environmental and economic results, presented on hourly, monthly and yearly bases.

4.1. Daily Analysis

The following Figure 2 reports some interesting temperature data in a typical winter and summer day. In particular, the trend of water temperature flowing from the solar collectors (coll), the tank top (tank) and the auxiliary heater (AH) are shown and compared to the trend of the digester inlet water temperature (dig).

For the selected winter day, during the night the ambient temperature is always below 10 °C and due to the unavailability of the solar radiation the auxiliary heater is provided to heat the digester inlet water and keep its temperature constant at 55 °C. It allows the realization of the desired mesophilic conditions inside the reactor. When solar radiation starts heating the ETC, T_{coll} increases involving the heating of the water in the tank. The auxiliary heater is turned off, and the water temperature T_{AH} exiting from it follows the same trend of T_{tank}. In the central hours of the day, T_{coll} overcomes the set point water temperature of 55 °C. In this case, the HE 2 dissipates the excess of the heat, preventing the overheating of the digester. In those hours, ETC thermal production is much higher than the digester demands, and the heat storge capacity has been completely used, too. This results in an overall increase of the solar loop temperature. A similar situation occurs during a typical day in summer, with the difference that the ambient temperature is always above 20 °C, reaching a maximum value of 30 °C around 15:00. Note that the HE 1 is always turned off, because the water temperature exiting the collectors is always below the set point temperature of 80 °C.

Figure 3 shows the thermal flow rate for a typical hot day in the summer and a typical cold day in the winter. The thermal power trend is consistent with the temperature trend shown in Figure 2. In summer, the digester thermal demand $\dot{Q}_{th,dig}$ is lower while the solar radiation is higher so that the auxiliary heater is almost always turned off except for the night-time hours. Conversely, the opposite trend is detected during the winter time, in which the auxiliary heater is completely turned off only in the central hours of the day. In both cases, the system is able to exploit the solar radiation, in fact, the thermal power supplied by the auxiliary heater $\dot{Q}_{th,AH}$ starts to decrease in the same moment in which it becomes different from zero, and some heat dissipation $\dot{Q}_{th,HE2}$ is required during the hottest hours due to the exceeding of the set point temperature of 55 °C. Note that the thermal power supplied by the tank $\dot{Q}_{th,tank}$ follows the same trend of one supplied by the collector $\dot{Q}_{th,coll}$. This means that the energy stored by the tank is never sufficient to satisfy the digester thermal demand, determining a higher energy demand to the auxiliary heater. It may be argued that the solar collectors are oversized, while the designed tank volume is insufficient to match the heat demand.

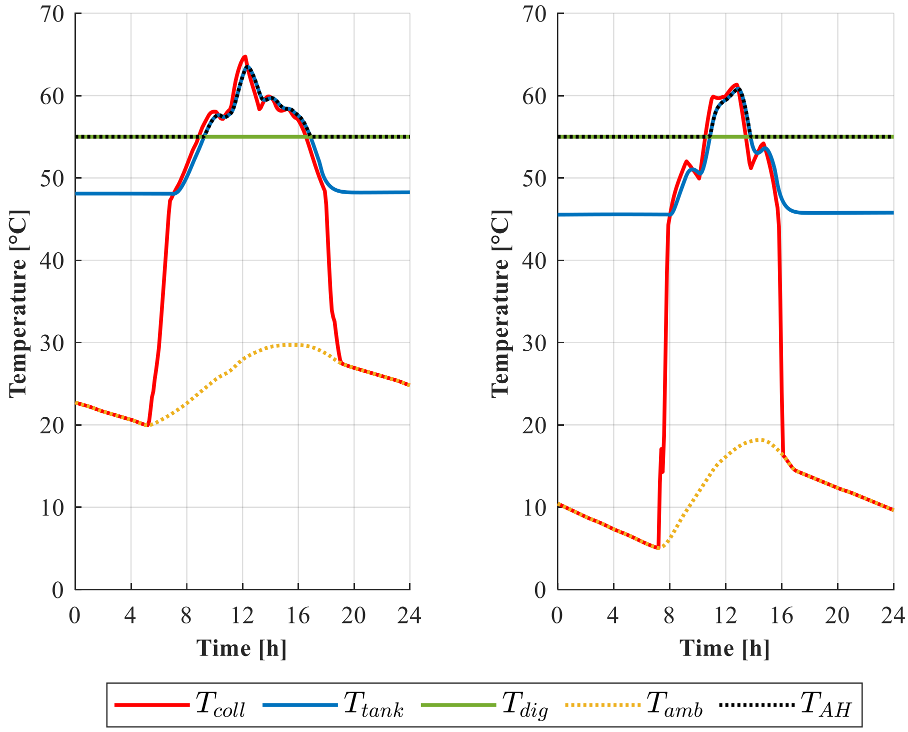


Figure 2. Temperatures for a typical summer (**left**) and winter (**right**) day.

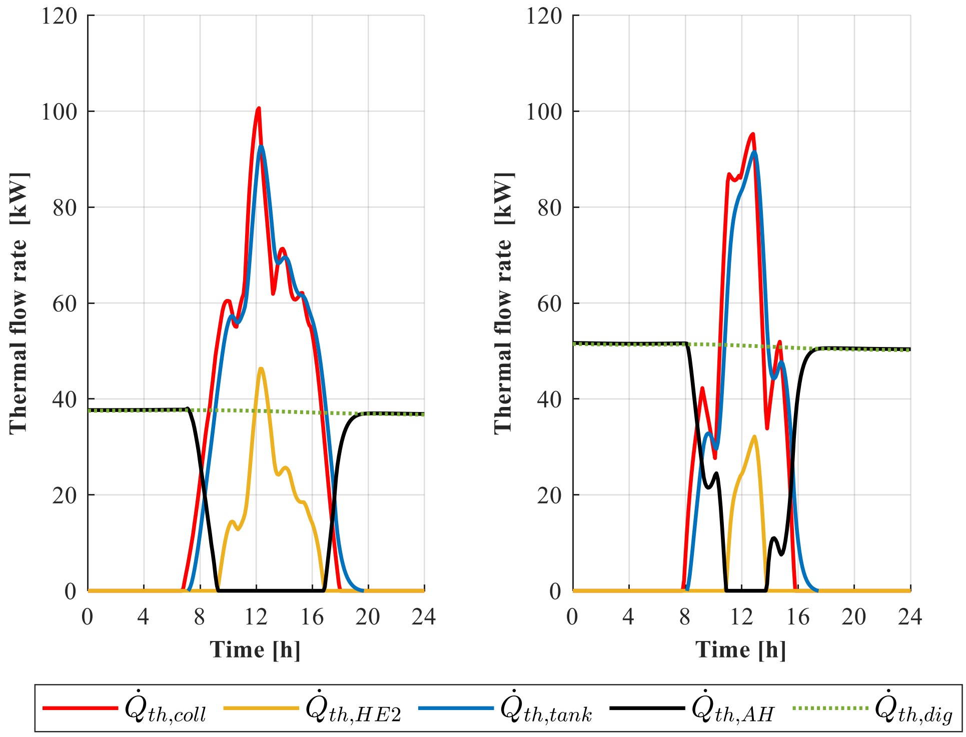


Figure 3. Dynamic results for thermal flow rates in typical summer (**left**) and winter (**right**) day.

A similar analysis can be performed for the results shown in the following Figure 4.

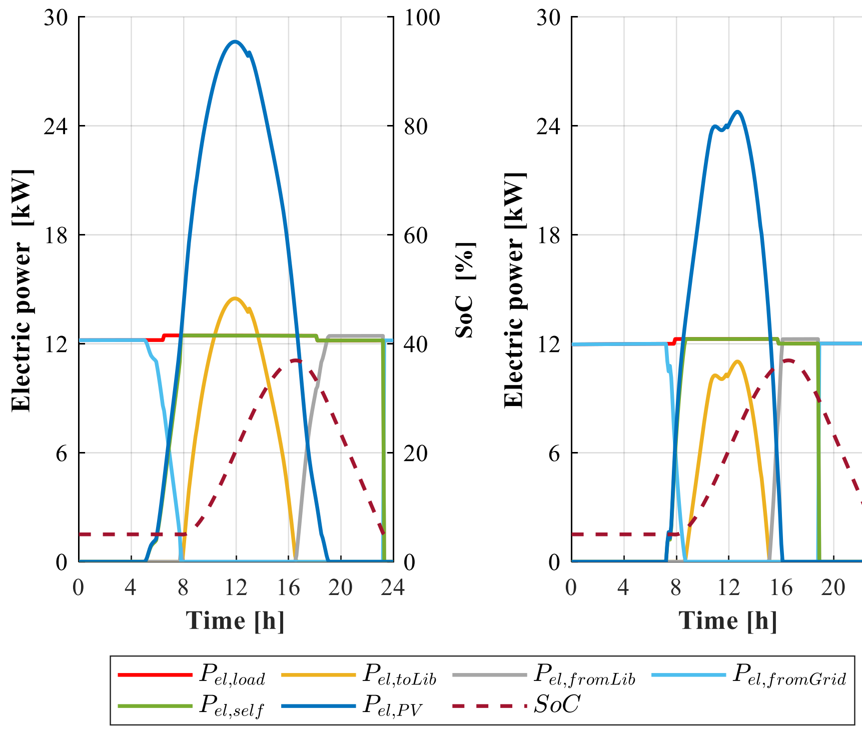


Figure 4. Dynamic results for electric powers in typical summer (**left**) and winter (**right**) day.

The electric power to load $P_{el,load}$ must match the electric demand of the pumps and the upgrading unit. It is almost constant and equal to 12 kW. The small step in the central part of the day is due to the activation of the P1, which turns on when the solar radiation starts. In these hours, the photovoltaic field power production $P_{el,PV}$ matches the plant power demand. During the remaining part of the day, the power demand of the plant is matched by the electric power withdrawn from the grid $P_{el,fromGrid}$. In Figure 4, SoC represents the state of charge of the lithium-ion battery. In summer, SoC is roughly equal to 40%, allowing the system to be self-sufficient all night. In winter, due to the low solar availability, the plant is self-sufficient only for about 3 h, from 16:00 to 19:00, withdrawing the electric energy from the grid for the remaining night-time hours. However, the battery never reaches the maximum allowed SoC of 95%. It means that the plant is not able to completely exploit the charge/discharge depth of the battery, and the electric energy storage system is resultantly oversized.

4.2. Monthly Analysis

The following figures report the monthly date analysis for the thermal (Figure 5) and electric energy (Figure 6).

As expected, the higher ETC thermal energy production occurs in the summer period, while the thermal energy required for the digester obviously reaches its minimum value. The digester thermal energy demand basically depends on the ambient temperature: the higher the ambient temperature, the lower the digester thermal energy losses and the thermal energy required for heating the inlet mass flow to the digester. Note that the curves relative to the thermal energy supply by the collector and by the tank are, practically, superimposed for the whole year.

The above discussed results are even more clear by analyzing the second graph. In Figure 5b, the black line displays the ratio of the thermal energy supplied by the AH and the total energy required by the digester. The red line represents the ratio between the thermal energy supplied by the ETC and the digester thermal demand. $E_{th,coll}$ meets more than 50% of $E_{th,dig}$ from June to September, but the majority of $E_{th,dig}$ comes from the AH. The grey line represents the ratio between the share thermal energy provided to the digester by renewable sources ($E_{th,dig} - E_{th,AH}$) and the $E_{th,coll}$. This line is always above 50%, implying that the renewables' contribution is mainly due to the collector and only in small part to the tank. The monthly analysis of the results also confirms that the tank is under-dimension, and its limited capacity does not allow the storage of the excess of the thermal energy provided by the ETC.

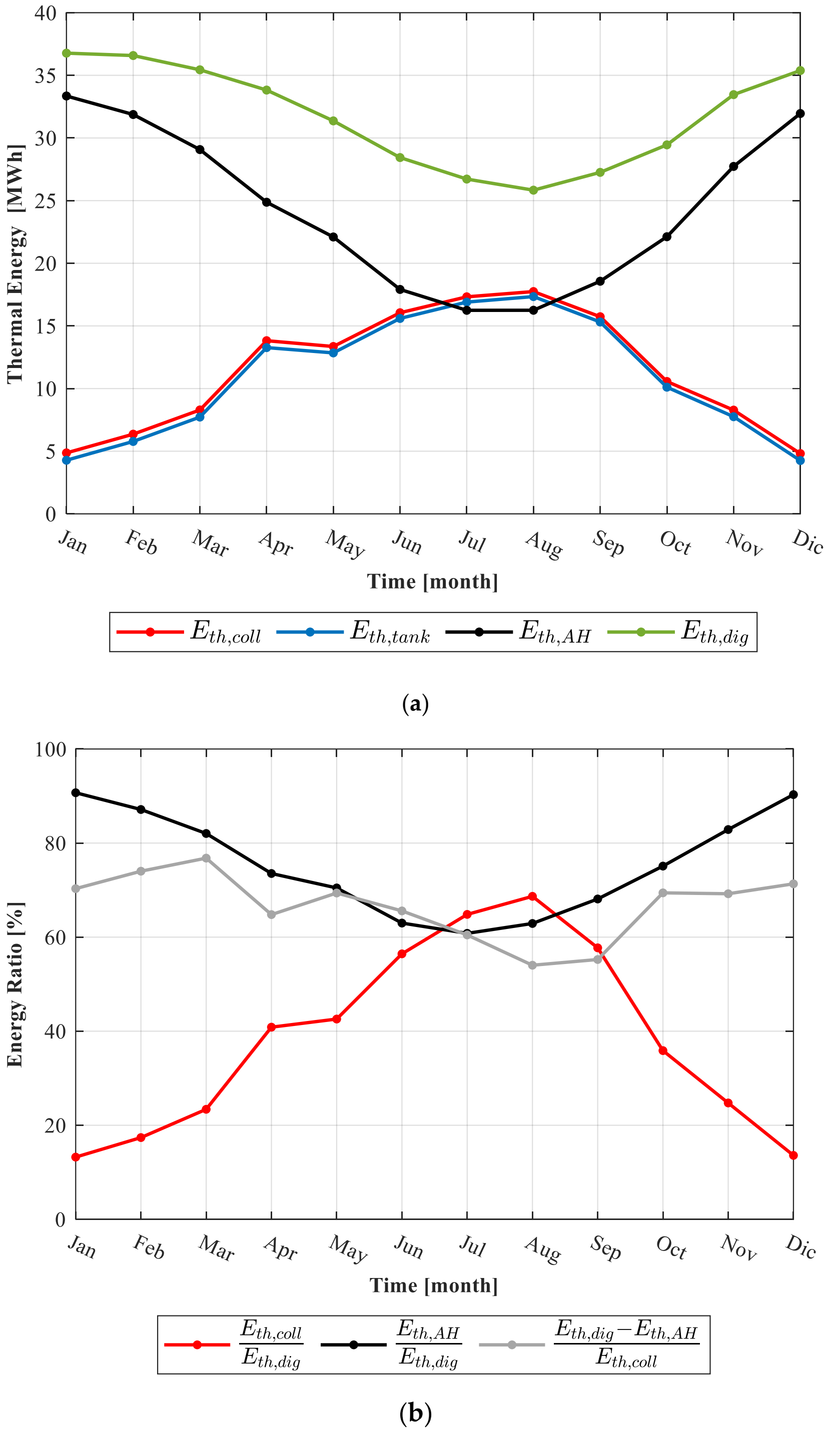
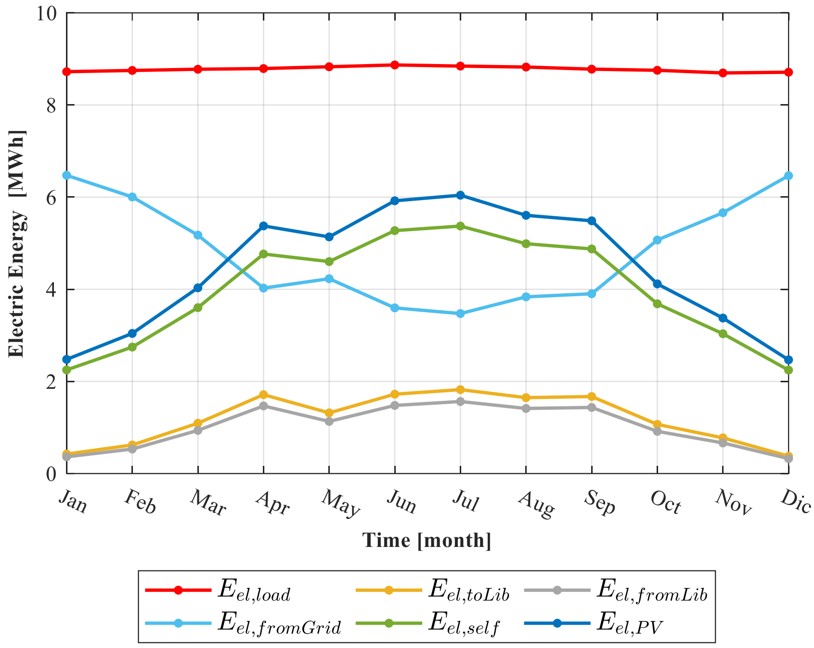
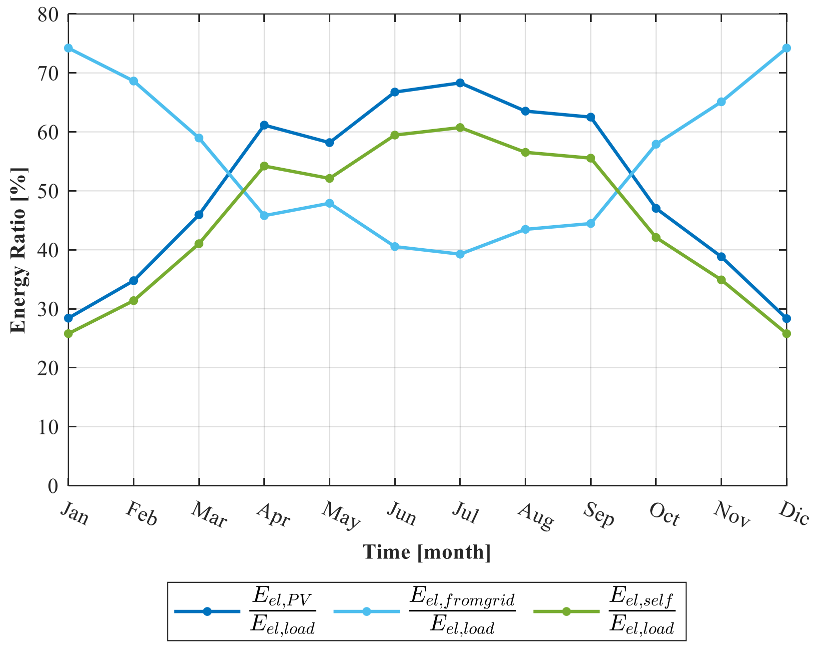


Figure 5. Monthly results for thermal energies (**a**) and thermal energy ratios (**b**).



(**a**)



(**b**)

Figure 6. Monthly results for electric energies (**a**) and electric energy ratios (**b**).

The electric energy demand of the plant is mainly due to the electric energy needed for driving the upgrading unit. It depends on the produced biogas mass flow rate that is constant during the whole year and equal to approximately 2000 Nm^3/d. The increased demand for electric energy from the grid occurs during the winter months when the solar radiation is scarcely available. The system is dependent on the grid due to the limited capacity of the battery. Note that, in Figure 6a, the electric energy injected into the grid is not reported because it is always null; the electric energy storage in the battery is completely used as a contribution to meet the digester demand.

4.3. Yearly Analysis

The plant produces a volume of biogas roughly equal to 800 × 10^3 Sm^3 per year, which corresponds to approximately 525 × 10^3 Sm^3 per year of biomethane. This result is consistent with the result reported by Calise et al. [67], reporting a case study for a continuously stirred tank reactor having the same volume and the same inlet waste flow rate.

In Table 4, the annual thermal and electric energy values are reported. The thermal energy supplied by the AH system is higher than the energy supplied by renewables and the system results yet is strongly dependent on the grid. In particular, the thermal energy supplied by the ETC meets approximately 35% of the thermal energy demand of the digester while the electric energy supplied by the PV meets over 50% of the electric demand of the plant.

Table 4. Yearly values of energy parameters.

Parameter	Value	Unit
$E_{th,dig}$	380.52	MWh/y
$E_{th,ETC}$	137.19	
$E_{th,AH}$	292.04	
$E_{el,load}$	105.34	
$E_{el,PV}$	53.08	
$E_{el,fromGrid}$	57.91	
$E_{el,self}$	47.43	

In terms of energy performance, the technology used in the proposed system has better performance than the concentrating photovoltaic/thermal collectors. In a previous work of the authors [67], a C-PV/T field of 96 m^2 was considered to meet the energy demand of the digester and the biogas upgrading unit, which elaborated the same biogas flow rate. In that case, it resulted that the C-PV/T was not convenient since the thermal energy production was overwhelming with respect to the electricity production. Since the major necessity in the peak production hours is of electric energy, the technology is not adequately exploited. In the work of Hao et al. [60], instead, a biogas upgrading plant with chemical absorption is powered for approximately 12% of its need through C-PV/T collectors. In this case, the plant capacity is higher, and the influence of the variations of the environmental conditions on its electric efficiency could be investigated.

The efficiency of the solar field can certainly be improved. The results provided by Darwesh et al. [61] show that 75% of the thermal demand of the anaerobic digestion plant in a mesophilic condition can be obtained with evacuated solar tube collectors. However, it is necessary to highlight that the study referred to is of an experimental plant of small size located in Egypt where the environmental temperature is more favorable for the process.

The Table 5 reports the capital cost of each plant component. The higher investment is represented by the digester cost. It represents almost 83% of the total investment.

In conclusion, the results of the thermoeconomic and environment analysis are reported in Table 6.

While a reference system would be necessary for a comparison from the environmental point of view, the economic results are very promising. The profitability of a plant depends on several variables such as the size of the plant, the type of incentive, the value of the incentive, the selling price of biomethane and the net revenue associated with the treatment of OFMSW [69]. The results obtained are in line with other works in the literature. In the work of Lombardi et al. [52], a plant processing OFWSW, in the same mesophilic and environmental conditions, obtained the same biogas flow rate. Different renewable technologies are integrated. In this work, a photovoltaic field has also provided for its electric energy demand. However, the proposed system has greater economic feasibility, presenting a SPB of 7.5 years since the plant analyzed in [52] is characterized by a greater digester volume and, therefore, by a larger solar field area. At the same time, in [52] the authors concluded that the incentive mechanism is a fundamental support to the economic sustainability of an AD plant. In this work, the public incentives acknowledged to the biomethane produced and injected into the public gas grid have been considered, indicating with the subscript "CIC" (Certificates of Emissions of Biofuels in Consumption) the obtained results. The value of 1CIC is 375 EUR, and the CIC number is evaluated as following:

$$N_{CIC} = \frac{V_{bio\mathrm{CH}_4} LHV_{bio\mathrm{CH}_4}}{5814} \quad (22)$$

In particular, the SPB can be reduced to approximately 5 years considering that the obtained incentive PI is higher than 100%.

Table 5. Capital costs.

Parameter	Value	Units
INV_{ETC}	60	k€
INV_{PV}	86	
INV_{dig}	3900	
INV_{TANK}	8.6	
$INV_{upgreding}$	630	
INV_{AH}	6.4	
INV_{P1}	342.92	€
INV_{P2}	318.85	

Table 6. Results from thermoeconomic and environmental analysis.

Parameter	Description	Value	Units
INV_{TOT}	Total capital cost	4650	€
M	Annual maintenance cost for the plant	46	€/y
PE	Primary energy consumed by the system	125	MWh/y
MCO_2	CO_2 emission produced by the system	60.80	tons/y
SPB	Simply payback period	7.5	year
PI	Profit index	33.56	%
NPV	Net present value	1563	k€
SPB_{CIC}	Simply payback period with incentives	4.9	year
PI_{CIC}	Profit index with incentives	103.44	%
NPV_{CIC}	Net present value with incentives	4817	k€

A similar result to the one obtained in this work is the result in [70], where a techno–economic analysis of a hybrid solar–biogas plant was proposed. In that work, the SPB result was slightly higher than the one obtained in this work because of a larger use of solar energy and a slightly different energy surplus to sell. The CIC considered in the proposed work are crucial to obtain a much higher NPV, precisely 1.56M EUR against 0.35M EUR in work [70].

5. Conclusions

In this work, a dynamic simulation model of an anaerobic digestion process in a plug flow reactor in combination with renewable technologies is proposed. To describe the thermal and biological processes occurring in the reactor, a model implemented in the

Matlab environment is proposed. It is based on two important simplifications. It considers a constant composition of the waste, neglecting its variation during the year. On the other hand, the waste and biogas temperature has been considered homogeneous in every section of the reactor, adopting a one-dimensional model. These simplifications represent a limitation of the model and are the object of further studies. Their exceeding allows having results more in line with reality.

The analysis shows that the considered plant is able to produce approximately 525×10^3 Sm^3 for a year of clean biomethane that can be injected into the national gas grid. The integration of an ETC solar field is useful to reduce the heat supplied by the auxiliary heater, but it is necessary to increase the tank volume in order to make the plant more self-sufficient from the thermal point of view. The capacity of the PV field, coupled with the lithium-ion battery must be increased to make the plant almost grid-independent. The plant is economically profitable, especially in the case of public incentives, when the SPB is 4.9 years and PI is 103.44%. A further optimization procedure could be carried out to investigate the optimal solution in terms of the area of the solar collectors and photovoltaic field, and consequently to improve the capacity of the storage tank and the lithium-ion battery. However, the model represents a valid starting point to investigate the responses of the reactor to the changes in the environmental condition and their influence on biogas production. Moreover, the plant could be enlarged with a unit for the production of compressed natural gas or liquified biomethane that would result in an additional advantage from the economical point of view.

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Nomenclature

A	Area [m^2]
AD	Anaerobic Digestion
ADM1	Anaerobic Digestion Model n.1
AH	Auxiliary Heater
AwR	Alkaline With Regeneration
BABIU	Bottom Ash for Biogas Upgrading
C	Yearly costs
C-PV/T	Concentrated PhotoVoltaic/Thermal
CSTRs	Continuous Stirred Tank Reactors
c_p	Specific heat [kJ/kg K]
c_u	Unit costs
C_{Lib}	Battery capacity
DIG	Digester
ETC	Evacuated Tube Collectors
FPC	Flat Plate Collector
G	Solar radiation [W/m^2]
HE	Heat Exchanger
HRT	Hydraulic Retention Time [d]
INV	Capital cost
Lib	Lithium-Ion Battery
M	Maintenance costs
$\dot{m}$	Mass flow rate [kg/s]
n	Number of pipes

OFMSW	Organic Fraction of the Municipal Solid Waste
ORC	Organic Rankine Cycle
P	Electric power [kW]
P1-P2	Pump
PE	Primary energy
PFRs	Plug Flow Reactors
PSA	Pressure Swing Absorption
PTC	Parabolic Trough solar Collector
PV	Photovoltaic
P_p	Peak power
$\dot{Q}$	Thermal flow rate [kw]
SPB	Simple Pay Back
T	Temperature [°C]
t	time
UASB	Up-flow Anaerobic Sludge Blanket
U	Heat transmission coefficient [W/m^2 K]
$\dot{V}$	Volumetric flow rate
V	Volume
Greek Symbols	
η	Efficiency
ρ	Density [kg/m^3]
ρ_j	Kinetic of the reaction of the process
$v_{i,j}$	Biological coefficient
v	Specific volume
Subscripts and Superscripts	
amb	ambient
$bioCH_4$	Bio-methane
coll	collector
dis	Dissipation
dig	digestor
el	Electric energy
GN	Natural gas
i	About the component "i"
j	About the process "j"
th	thermal
tot	total
wc	Woodchip

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