

Experimental evaluation and data-driven modeling of a household anaerobic digester for waste-to-biogas conversion

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ABSTRACT

The paper describes the outcomes of a ten-months experimental campaign and a hybrid model aimed at characterizing a micro-biogas plant behavior under realistic operational conditions. Both the experimental data and the results of the simulation were used to estimate the plant's performance and the effect of equipping it with a thermal insulation system and a heating system to increase its internal temperature.

The results of the monitoring showed that the digesters produced an average of 170 l/d of biogas with an average methane content of 53% and a conversion efficiency of 84 kg of methane per ton of organic matter; moreover, it was observed that biogas production increased by 1.2 l/h or each additional 1 °C internal temperature. The results of the simulations showed that, in the base scenarios, the digester can produce an average of 0.98 kWh/d in the Mediterranean island of Lampedusa and of 0.32 kWh/d in the alpine village of Tarvisio. Thermal insulation alone showed a negative effect on digester temperatures and energy production. Solar base heating showed some benefits, while the best results were achieved through the combination of the two measures (+14.6% average internal temperature and +33.7% energy generation in Lampedusa, +22.9% and +69.0% in Tarvisio).

1. Introduction

1.1. Background

The current context is dominated by a growing awareness of ongoing climate change and its effects on both a global and local scale, coupled with the necessity of implementing mitigation and adaptation measures according to an integrated and multidisciplinary approach, favoring the sustainable development of energy, water, and environmental systems [1].

Greenhouse gas emissions are the primary cause of global warming, a phenomenon closely related to issues of energy production, land use, changing in lifestyle and consumption patterns that have influenced the relationship between people, the planet, and its resources [2]. The adoption of decarbonization policies and the consequent reduction of emissions have become global priorities to meet Paris Agreement goals, limiting the rise in global temperatures to 1.5 °C [3] compared to pre-industrial times.

At the same time, an estimated 789 million people worldwide still lack access to electricity, mainly in rural developing areas [4], creating a state of energy poverty [5] where households must spend a significant portion of their income to meet basic energy needs [6]. The use of inefficient and unsafe technologies and unclean fuels affects the quantity and quality of energy consumption, resulting in social, economic, and environmental costs, with consequent impacts even on human health (e.g., traditional cookstoves, causing black carbon emissions and indoor air pollution) [7].

Increasing renewable energy consumption and improving energy efficiency are globally relevant goals. In accordance with the Sustainable Development Goal 7 of Agenda 2030 [8], the adoption of sustainable and integrated approaches is particularly necessary where energy access and waste management represent significant challenges due to the absence of infrastructure and resources [9]. In this context, bioenergy is a key element in decarbonization pathways [10], as it can replace the use of conventional fuels in electricity and heat production. The exploitation of biomass or intermediate vectors such as biogas through

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Nomenclature**Abbreviations**

AD	Anaerobic digestion
ADM1	Anaerobic Digestion Model No 1
GHG	Greenhouse Gas
HEAT	Base heating
INS	Insulation

Symbols

α	Surface radiative absorption coefficient [–]
\dot{Q}	Heat flow [W]
\dot{V}	Volumetric flow [$\frac{1}{h}$]
η	Efficiency [–]
λ	Thermal conductivity [$\frac{W}{m\ K}$]
ρ	Density [$\frac{kg}{m^3}$]
c_p	Specific heat [$\frac{J}{kg\ K}$]
d	Thickness [m]
h	Convective heat transfer [$\frac{W}{m^2\ K}$]
q	Specific heat flow [$\frac{W}{m^2}$]
T	Temperature [$^{\circ}C$]
V	Volume [m^3]
v	Speed [$\frac{m}{s}$]
x	Molar concentration [–]

Superscripts and subscripts

cond	Conduction
conv	Convection
corr	Correction
dg	Digester
int	Internal
surf	Surface

combustion, anaerobic digestion, pyrolysis, or gasification technologies has contributed to covering 12% (45.2 EJ) of the total final energy consumption, representing 50% of the estimated potential and the highest share of global energy supply associated with a renewable source [11].

Within this framework, the present paper focuses on micro-scale anaerobic digesters fed with locally available food waste to be included as a part of the energy supply systems of individual households, hotels/restaurants and small communities.

1.2. Literature review

This section provides an overview of the existing literature relevant to the topic of this paper and highlights current research gaps. Section 1.2.1 examines the general field of biogas production, while Section 1.2.2 focuses on small- and micro-scale digesters. Section 1.2.3 is dedicated to literature on mechanical solutions aimed at enhancing biogas generation in small-scale systems. Finally, Section 1.2.4 explores existing modeling approaches for digesters.

1.2.1. Biogas

Biogas is a renewable energy source derived from the biological decomposition of organic matter in the absence of oxygen, known as the anaerobic digestion process. This gas is usually composed of 50%–75% methane (CH_4), 25%–50% carbon dioxide (CO_2), along with

other trace gases such as nitrogen, hydrogen sulfide, ammonia, and water vapor [12].

Biogas production primarily occurs through the fermentation of various biomass sources, including biodegradable waste (such as the organic fraction of municipal solid waste) [13,14], industrial and agricultural by-products [15–18], and wastewater [19–21].

From an energy perspective, biogas can be utilized for heat and/or electricity production through combustion in boilers [22] or internal combustion engines [23]. Additionally, it can be purified to remove carbon dioxide and other contaminants through separation processes and used as biomethane [12,24].

Biogas-related technologies and solutions have been often investigated to evaluate their contribution to national decarbonization pathways (see for instance Sica et al. [25] for Italy, Silaen et al. [26] for Indonesia and Kapoor et al. [27] for India and Wakeel et al. [28] for Pakistan). However, they are particularly suitable in contexts of energy or logistical isolation (e.g., rural, remote, and isolated areas, or small communities) where energy grids, if available, have limited capacity and/or stability. In Mauritius, it was estimated that anaerobic digestion of sugarcane residues and municipal waste could meet 12.6% of energy needs, reducing reliance on fossil fuels [29]. In Ghana, studies suggested that agricultural residues provide an energy potential four times higher than the current capacity (4.57 GW), with cocoa pod husks identified as an underutilized resource for energy generation [30]. In India, Shukla et al. [31] suggested that biomass conversion to biogas could meet 100% of energy demand in 55.6% of rural districts, while reducing PM2.5 emissions by 33%–85%. A study in Iran highlighted the adaptability of biogas systems to diverse rural contexts, considering social, climatic, and economic factors to develop tailored energy solutions for villages [32].

In such contexts, the availability of raw materials limits the capacity of the energy systems, which tend to have high specific investment costs due to economies of scale [12]. For actual implementation, possible barriers include limited experience in the construction, maintenance, and management of these technological systems; lack of adequate knowledge, training, and dissemination aimed at increasing the social acceptance; in some cases, low cost of fossil fuels available on the market; lack of appropriate business models [33].

1.2.2. Small- and micro-scale biogas generation

Unlike other technologies, anaerobic digestion systems are feasible at many scales, from centralized systems with capacities of thousands of cubic meters, as described earlier, to small digesters that produce enough biogas for a single household. Widely spread in many rural communities in Asia, Africa, and Latin America thanks to government or NGO support, small- and micro-scale systems generally do not require mechanical mixing or heating and produce biogas mainly used in stoves and lamps, generating environmental, health, and social benefits [34,35].

Advanced systems for the biological treatment of organic waste at the household scale are also under investigation [36]. A 60-day experiment on an anaerobic digester using food waste, wastewater, and sludge as inoculum achieved methane production of 0.299 liters of methane (95%) per gram of volatile solids, supported by optimized management and control strategies [19]. A hybrid bioreactor (anaerobic/semi-aerobic with leachate recirculation) treated 125 kg of material excluding non-biodegradable components, resulting in a methane production of 23.38 $kgCH_4/t$, and showing significant development potential [37].

Integrated multi-input multi-output energy polygeneration systems are rapidly spreading, offering complementary features in terms of production, modularity, costs, and impacts. Numerous studies have been conducted in various regions (e.g., Kenya, Spain, Brazil, Pakistan, India), starting from thorough analyses of available resources [38]. With reference to small-scale devices, an example includes an integrated system with 3 kW_{PV} and electrical storage, a 7 m^3 biogas

digester (producing 4 m³/day) fed by local animal/agricultural waste, coupled with an internal combustion engine; this electrical generation setup can meet the energy needs of a 4-5-room household [39]. For a similar system, Pal et al. [40] investigated the monthly variation in biogas production (based on average daily temperature) and a control strategy to minimize the probability of failing the required load.

1.2.3. Mechanical improvements of small-scale anaerobic digesters performance

The use of manure as a reaction starter that supplies microbes and organic material to the digester is particularly convenient due to manure being cheap and easily available in a wide range of context. However, the metabolism of mesophilic bacteria is known to slow or even halt below 20 °C–25 °C [41], which requires that digesters should be stored indoors and/or heated to maintain efficient operating conditions during the cold season. However, most solutions to control temperature are expensive and energy-intensive, making them unsuitable for small-scale digesters.

Several passive or low-cost solutions have been proposed in academic literature [42–44]. Some of these are, however, not applicable in residential and/or remote contexts, such as the use of co-digestion or additives, the adaptation of the inocula and the modification of the feed.

Insulating the digester can be a cheap solution, but evidence of the effects of its use is mixed. Twizerimana et al. [45] showed that simply covering the digester with a 12 cm-thick layer of sawdust improved the biogas yield by 80% compared to the reference case with no insulation, while Anand and Singh [46] found that coating the ground around the digester with charcoal allowed improving gas production by 7 to 15%.

A small greenhouse can be a cost-efficient solution to improve biogas production in cold climates. This was solution was applied to an underground digester by Hassanein et al. [47], who observed an increase of 9.8 °C in the average yearly digester temperature; Kumar and Bai [48] also found improvements when using a greenhouse, in this case applied to an above-ground digester in a hilly region in India, observing a 4 °C increase in internal temperature and a 40% increase in gas yield. Even better results were presented by Bansal et al. [49], whose numerical simulation showed an increase of internal temperature from 18 °C to 37 °C when using a greenhouse.

Finally, some authors have also suggested the use of direct heating to ensure sufficient internal digester temperatures: Jia et al. [50] proposed the use of an electric heater, which could be coupled to a PV panel; Tan and Wang [51] proposed the combination of solar energy and a biogas boiler.

1.2.4. Anaerobic digestion in energy systems models

Anaerobic digestion systems are relatively well known technologies, and there is extensive literature concerning their modeling. An extensive review was published by Emebu et al. [52], to which the interested reader is referred for a detailed analysis of the existing methods for anaerobic digestion modeling.

As reported by Emebu et al. [52], modeling approaches for anaerobic digestion can be categorized as follows:

- Dynamic single-equation models
- Cumulative single-equation models
- Multi-regression single-equation models
- Multi-step dynamic degradation models

Multi-step dynamic degradation models are often too detailed to be included in wider energy systems models, especially given that the added detail is often not required by the modeler. They require detailed knowledge of the system underlying phenomena and of the input, which is often unknown when not dealing with a specific case study. Also, while this is not the leading reason to discard them in energy system models, they have higher computational requirements [53].

Nevertheless, a simplified version of the Anaerobic Digestion Model No 1 (ADM1), developed by Batstone et al. [54] in collaboration with the International Water Association, was used by, among others, Vergote et al. [55] to evaluate the potential of farm-scale digestion to reduce GHG emissions, and by Strubbe et al. [56] to evaluate the potential of small-scale digesters in Rwanda.

While being an important factor in AD, temperature is not considered as a dynamic state variable in most publications on AD models [52]. This can be partly explained by the fact that large-scale digesters, often the focus on scientific research on the topic, work at a fixed temperature (a reasonable approach in large systems where the system's temperature is monitored and controlled). This is not the case, however, for micro-scale systems, such as the one modeled in [56] (who uses ADM1, that includes temperature-dependent parameters) and the one that is the object of this study. Micro-scale (or household-scale) anaerobic digesters have high surface-to-volume ratios, are poorly insulated, and do not have any temperature-control system. Hence, their performance strongly depend on the internal temperature, which varies widely during the year depending on the climate.

Other authors use simplified models to reduce the complexity of the system while retaining a sufficient modeling accuracy. Figaj [57] proposes a small-scale hybrid renewable energy system powered by biogas, solar energy, and wind, and its model-based techno-economic analysis; in his model, Figaj uses a modified version of the Gompertz function, as originally proposed by Zepter et al. [58], which in turn is based on the work by Cordoba et al. [59]; this modeling approach is simple and effective, but is based on the assumption of working at a fixed temperature (a reasonable approach in large systems where the system's temperature is monitored and controlled) and on the knowledge of often unknown input data, such as the organic fraction of the input biomass.

1.3. Aim

For the reasons outlined in the previous Sections, difficulties in accessing robust logistical and technological infrastructures for the installation and management of large-scale biogas plants drive the investigation of small-scale solutions, which must strike a balance between costs and benefits.

However, as shown in the review of the existing literature, there is a clear research gap related to small and micro-scale digesters. More specifically:

- many studies (e.g. [45,60]) base their results on lab-scale experimental reactors, while there are only few results related to commercial products;
- most studies are either experimental or numerical, but do not combine both approaches;
- most papers look into hot or tropical climates, while only few (e.g. [43,48,49,61]) look into these systems' performance in cold or temperate climates;
- few studies focus on developed countries, with the consequence that most work assumes the use of animal manure as biomass feed, while very few look into organic household waste.

This paper aims at addressing this gap, by providing both the results of an extensive experimental campaign, and a simplified model of the small-scale digester appropriate to be used in household-level system models. The data collected during the experimental campaign were used to validate a model of the installed system, which allows to provide reliable performance predictions, identify optimization measures and potential adaptation to other contexts, thus serving as a valuable decision-support tool.

More specifically, compared to other studies in the literature, the added value of the results presented in this article lies in the following aspects:



(a) Digester

(b) Base heating plate

Fig. 1. Experimental facility.

- Long-term experimental campaign and use of a monitoring system for biogas production parameters, typically reserved for large-scale plants, whose absence has been identified among the main factors of failure due to lack of preventive and corrective maintenance [35].
- Evaluation of the potential benefits deriving from the adoption of thermal insulation and solar heating to increase the digester's internal temperature.
- Real operating conditions, with organic load associated with actual users.
- Limited direct and indirect interventions on biogas production parameters and process stability (e.g., pH, Carbon and Nitrogen content and their C/N ratio, concentration of volatile fatty acids, retention time, etc.), resulting in extreme ease of installation, operation, and maintenance, ensuring the best replicability of the proposed solution.
- Development of a model for simulating the biogas system, based on real operating conditions.

1.4. Paper structure

To address the scientific gap as stated in Section 1.3, the study was divided in three main stages. First, the production of biogas from an experimental facility was monitored for an extended period of time, as explained in Section 2.1. The data collected during the monitored period was used to calibrate a hybrid model, described in Section 2.2. The results are presented in Section 3: the analysis of the data obtained during the monitoring phase (Section 3.1), and the application of the calibrated model to two case studies are presented (Section 3.2). Finally, the results and the method are discussed in Section 4, and the conclusions are presented in Section 5.

2. Methods and materials

To address the research gap, we proposed a mixed experimental-modeling approach, where an extended experimental campaign (see Section 2.1) was used to gather data about the biogas production from a specific digester. The data was then used to define and calibrate a simplified, gray-box numerical model of the digester (see Section 2.2), that was used to derive more general conclusions about the performance of different solutions to improve the productivity of these systems, and on how they can be expected to perform in different climatic conditions.

2.1. Experimental setup

An experimental facility was set up with a biogas production unit, equipped with a monitoring system that allowed to gather information with respect to system temperature, gas production quantity and quality. These parameters (e.g., internal temperature, biogas production rate, and methane content) have been selected on the basis of both literature (e.g. [47,48]), and the specific characteristics of small-scale biogas systems (e.g., [39,40]). They are directly correlated to the biological performance of the digester and the energy potential of the produced biogas. The facility was operated and monitored from the 1st of May 2023 to the 28th of February 2024. During this period, the biogas production units were regularly fed with waste coming from a local holiday farmhouse, where the system was installed.

2.1.1. Biogas production unit

The biogas production unit is built around the core of two Homebiogas™ digesters (hereinafter called Digester 1 and Digester 2), each made of a digester tank of 2000 l volume and a 700 l gas storage tank (Fig. 1(a)). According to the manufacturer's information, each of them can be fed with up to 4 l of kitchen waste per day. A 2000 l gas storage bag was added to the base system to minimize the amount of gas wasted as over-production.

Both digesters are equipped with a heating plate, positioned underneath the bottom of the digester, that allows circulating a flow of hot water to increase the internal temperature, if required (Fig. 1(b)). The experimental setup allows water heating through thermal solar panels (3 m² of total installed surface, South-oriented, 35° tilt); the solar system's pump is automatically activated as soon as the temperature of the water in the panels rises above 30 °C, thus heating up the thermal storage. This allows, in turn, to provide hot water to the heating plates at a temperature ranging between approximately 20 °C during winter up to 40 °C during summer; the pump of the water system connected to the heating plates is manually controlled. The solar thermal panels used in the system were recovered from a previous installation. The thermal solar technology was chosen because it is less complex and costly compared to electricity-powered systems, thus more suitable for small-scale operations.

Digester 2 was also equipped, for a period of 45 days during the winter season (13/01/2024 to 28/02/2024), with an external insulation layer to test its potential to improve the internal temperature conditions. The thermal insulation is made of a 5 cm layer of mineral wool, contained inside a plastic layer to protect it from the weather.

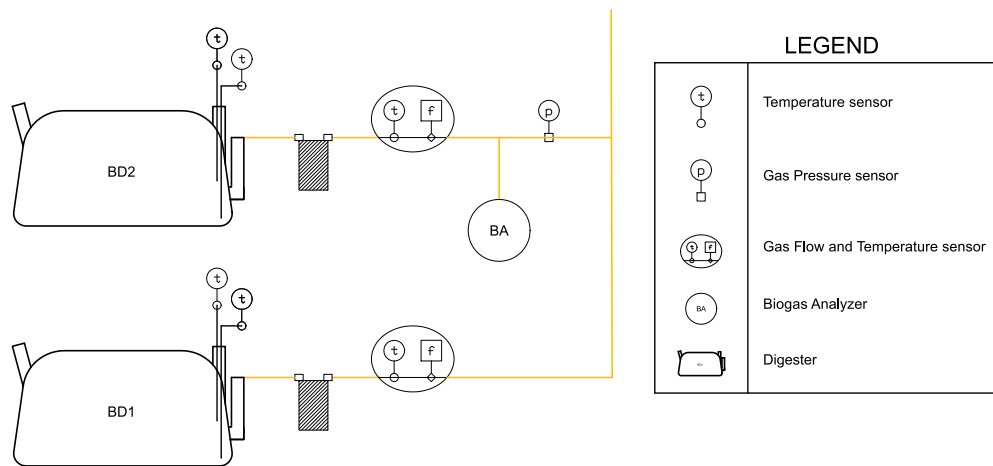


Fig. 2. Schematics of the test rig.

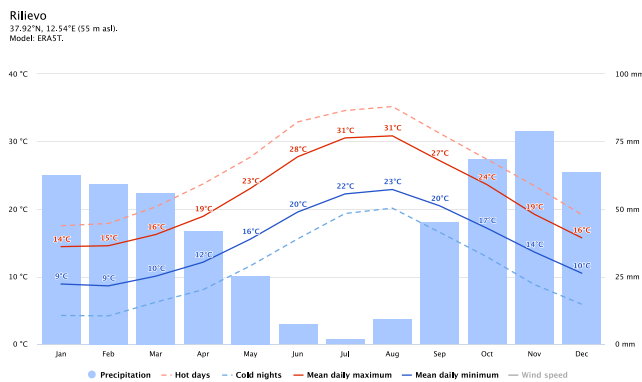


Fig. 3. Typical climatic conditions of the location of the experimental facility. Meteoblue.com elaboration of ERA5 data.

2.1.2. System monitoring and data acquisition

Both digesters are equipped with the following monitoring sensors:

- a thermal mass flow meter, calibrated for a 50%CH₄-50%CO₂ gas mix;
- a PT500 temperature probe located at approximately mid-depth within the digester, measuring the internal digester temperature;
- a PT500 temperature probe located at the bottom of the digester, measuring the temperature of the internal surface of the digester facing the ground/heating plate;
- a gas quality analyzer, able to measure the concentration of CH₄, CO₂ and H₂S in the biogas for Digester 2.

The specific position of all the sensors is shown in Fig. 2. All the data was collected using a CR6 Campbell Scientific data logger.

In addition, a weather station was also available for advanced ambient conditions monitoring between 01/01/2024 and 13/04/2024.

2.1.3. Location

The experimental facility is located in Misiliscemi, in the province of Trapani, Sicily – Italy. The location enjoys a relatively mild climate, as shown in Fig. 3. It can be observed, however, that the average temperature can be lower than 15 °C for several weeks during winter, potentially bringing the system to operate in non-appropriate conditions.

2.1.4. System management and control

With the aim of analyzing the actual operating conditions of a microscale digester installed outdoors to serve a domestic user in a mild

climate (Italy), the authors chose not to operate any conditioning regarding the quality and quantity of the available food waste. Although the physical parameters and biochemical composition are extremely variable [62], limited chemical information on the elements composing the organic fraction (carbohydrates, proteins, lipids) does not provide clear indications regarding biogas production effects [63].

The food waste used to feed the digesters was provided by the staff of the farmhouse where the system was installed, based on availability. The staff was instructed to avoid components that could slow down or inhibit the degradation process of organic residues were also excluded e.g., fish bones, lignocellulosic material, pesticide residues, pharmaceutical products, etc. [64]. Equal quantities of waste were introduced in both digesters for each waste addition. In addition, every time the digesters were fed, enough water was added to replenish them to their full capacity.

Seeking to limit and simplify direct user action, attention focused on the operational conditions of the digester, whose thermal performance is supported by the presence of an insulation system and solar heating plates as explained below, less complex and costly to install and maintain compared to electricity-powered systems, thus more suitable for small-scale operations.

Among all different operational settings, internal temperature is known to be the one that affects productivity the most. The formation of biogas is associated with different temperature regimes, varying in their advantages and disadvantages: psychrophilic (10-20 °C), mesophilic (20-40 °C), and thermophilic (50-65 °C). Higher temperatures are associated with higher CH₄ content, faster reactions, but also with increased risk of instability. Regardless of the temperature range, it is essential to maintain it at an approximately constant level, as any temperature fluctuation can adversely affect the entire process [65].

For the system used in this study, the manufacturer recommends that the operating temperature of the system be always kept above 15 °C. In order to investigate the effects of heating and insulation on the digesters' internal temperature and productivity in different seasons, these systems were applied during different periods, as detailed in Table 1.

2.2. Digester modeling and simulation

As explained in the introduction, one of the objectives of the study is to provide a simplified model of the digester's biogas generation, both in terms of flow and of methane content, in situations when the input biomass flow is not known and, hence, cannot be included in the model as an independent variable. To be used as part of wider small-scale polygeneration systems models, the proposed model should be able to predict the required output based on the location's climatic conditions.

Table 1
Summary of the simulated scenarios.

Period	Digester 1	Digester 2
01/05/23–14/07/23	HEAT	HEAT
14/07/23–04/08/23		
04/08/23–21/12/23	HEAT	HEAT
21/12/23–01/01/24		
10/10/24–13/01/24	HEAT	
13/01/24–23/01/24	HEAT	INS
23/01/24–28/02/24		HEAT, INS

An additional requirement is for the model to be dynamic, in order to allow understanding how the biogas production and storage can be integrated with other local energy generation means.

2.2.1. Model definition

Conceptually, the model was designed to be divided in two parts:

1. The thermal balance of the digester, to determine the digester's internal temperature
2. The functions correlating the output biogas flow \dot{V}_{biogas} and its methane content $x_{CH_4,biogas}$ to T_{bdg}

The thermal balance is modeled using the system of Eqs. (1) to (4).

- Eq. (1) is an empirical equation that allows providing an estimate of the convective heat transfer coefficient h_{conv} between the surface of the digester and the external environment, and on its dependence on the wind speed v_{air} . This is considered to be a useful inclusion in the model, as micro-scale digesters are often placed outside (in gardens and yards) and the heat loss can be influenced by the intensity of the wind. The choice of the correlation, originally proposed by Siple and Passel [66], is justified but its simplicity and its relatively widespread use (it is used, for instance, in the ASHRAE Handbook [67]).
- Eq. (2) allows calculating the external surface temperature $T_{dg,surf}$ of the digester, based on the balance between conductive, convective and radiant heat transfer contributions. This expression is based on the assumption of concentrating the whole thermal inertia of the digester system in the digester's content, which is considered to be reasonable when comparing the mass of the empty digester shell (a few kg) to the mass of the digester's content (approximately 2000 kg).
- Eq. (3) allows calculating the conductive heat transfer through the digester's shell \dot{Q}_{cond} , based on the digester's shell transmittance $\frac{\lambda}{d}$.
- Eq. (4) allows updating the internal temperature of the digester $T_{dg,int}$ based on the thermal balance of the digester's content, where the only contributions are the heating through conduction \dot{Q}_{cond} and the external base heating \dot{Q}_{HEAT} . It is here assumed that the base heating is available as an external measurement, and that it is measured at the inlet/outlet connection of the heat source: hence, a heating efficiency η_{HEAT} is added to the equation to account for losses. This choice was based on available data, but it implies no loss of generality.

Biogas generation reactions are, overall, exothermic, and their contribution should theoretically be added to Eq. (4). However, during early tests of the model, we verified that the contribution of the chemical process of anaerobic digestion to the overall thermal balance of is negligible in systems of this size. This is because of the small size of the system, the low operating temperature, and the high impact of external conditions (solar radiation, conduction and convection losses). Therefore, this component of the heat balance was not included in Eq. (4). This choice is also in line with similar studies, such as the work presented by Curry et al. [68].

$$h_{conv} = (9 - 0.862v_{air} + 8.62\sqrt{v_{air}})k_{corr,conv} \quad (1)$$

Table 2
Calibration results for the thermal model of the digester.

Parameter	Symbol	Unit	Value
Heat loss surface	A	m^2	4.8
Convective heat loss coefficient corr. factor	$k_{corr,conv}$	–	1.08
Conductive thermal resistance (outer shell)	$\frac{\lambda}{d}$	$\frac{W}{m^2 K}$	$1.50 \cdot 10^{-3}$
Surface radiative absorption coefficient	α	–	0.254
Base heat exchanger efficiency	η_{HEAT}	–	0.519

$$T_{dg,surf} = \frac{\alpha \dot{q}_{solar} + h_{conv} T_{amb} + \frac{\lambda}{d} T_{dg,int}}{(h_{conv} + \frac{\lambda}{d})} \quad (2)$$

$$\dot{Q}_{cond} = \frac{\lambda}{d} A (T_{dg,surf} - T_{dg,int}) \quad (3)$$

$$T_{dg,int}^{t+dt} = T_{dg,int}^t + \frac{\dot{Q}_{cond} + \dot{Q}_{HEAT} \eta_{HEAT}}{\rho c_p V} dt \quad (4)$$

To solve the system of Eqs. (1)–(4), different input variables and parameters are required. v_{air} , $\frac{\lambda}{d}$ and \dot{q}_{solar} are expected to be available either as direct measurements (as it was done, in this study, to calibrate the model) or in the form of location specific climatic data. The volume of the digester is set to $2 m^3$ based on the system's technical data, while the internal fluid's density ρ and specific heat c_p were assumed to be those of water (respectively $1000 \frac{kg}{m^3}$ and $4187 \frac{J}{kg K}$) for simplicity. The parameters A , α , $k_{corr,conv} \frac{\lambda}{d}$ and η_{HEAT} were subject to calibration, based on available measurements from the experimental facility.

Finally, the biogas production (expressed in liters of biogas per hour) and quality (expressed in % of methane content) were modeled using empirical correlations, calibrated using data measured from digester 2. For both variables, three different functions were tested, provided in Eqs. (5) to (7):

$$y = a_0 + a_1 T \quad (5)$$

$$y = y_0 + \Delta y (1 - e^{-b(T-T_0)}) \quad (6)$$

$$y = y_0 + \Delta y \tanh(b(T - T_0)) \quad (7)$$

In the case of the methane quality, it was observed from the monitoring that it is influenced by past temperatures, and not only by the current temperature inside the digester. For this reason, the average past temperatures were used instead of the current temperature, over an interval whose duration was subject to calibration.

2.2.2. Model calibration

To maximize the exploration of the parameter space and reduce the risk to incur in local optima, a genetic algorithm was used, with the objective to minimize the mean absolute error (MAE) between the measured and predicted values.

All measured variables required for the thermal model calibration were available from digester 2's monitoring available from the period between the 02/01/2024 and the 28/02/2024. This period is particularly relevant since, as shown in Table 1, it includes all possible combinations of digester 2 being insulated and heated, or not. The period between the 05/01/2024 and 21/02/2024 was initially used as calibration dataset, while the remaining periods were used for model validation. Once the validation proved successful, the whole available dataset was used for a final calibration step, to maximize the usage of the data.

The results of the calibration of the thermal part of the model are shown in Table 2, while the goodness of the fit between measured (M) and calculated (C) values is shown in Fig. 4. The figure allows observing how the proposed thermal model, once calibrated, allows a very good fit and well reproduces both daily and longer-term temperature variations.

For the relationship between digester internal temperature, biogas production and methane content, the calibration procedure was repeated 10 times for each alternative. The average MAE across the

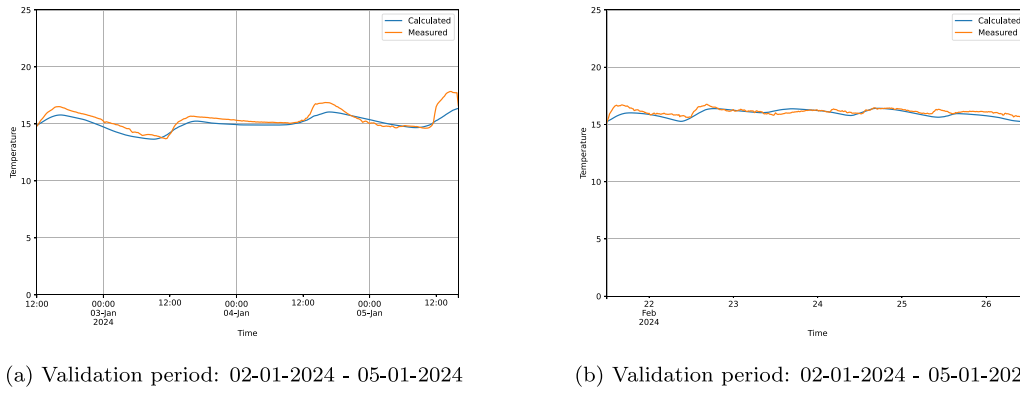


Fig. 4. Results of the validation of the thermal model.

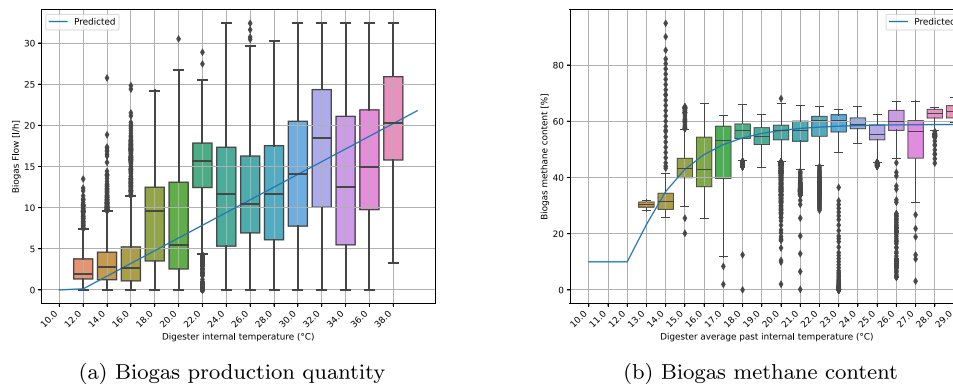


Fig. 5. Modeled relation between biogas production quality and methane content, and digester internal temperature.

Table 3
Average MAE across calibration repetitions for the different functions.

	\dot{V}_{biogas}	x_{CH_4}
Lin	5.09	6.76
Exp	5.08	4.87
Tanh	5.08	5.08

repetitions of the calibration procedure is shown in Table 3. Based on these results, it was chosen to use the linear function to model the biogas production, while expression (6) was used to model the methane content in the biogas. The calibrated expressions are shown in Eq. (8) and Eq. (9):

$$\dot{V}_{biogas} = -9.15 + 0.773T_{dg,int} \tag{8}$$

$$x_{CH_4} = 0.269 + 0.320 \left(1 - e^{-0.400(\bar{T}_{dg,int} - 286)} \right) \tag{9}$$

where the average past temperature \bar{T} used in Eq. (9) is set to 7 days. The resulting relation between biogas production quality and quantity, and digester internal temperature, is represented in Fig. 5, together with a box plot representing the distribution of the measured data to show the model accuracy. In both relations, a minimum and maximum value (respectively $\dot{V}_{biogas,min}$ and $\dot{V}_{biogas,max}$ for the biogas flow and $x_{CH_4,min}$ and $x_{CH_4,max}$ for the methane content) were included in the relation, based on minimum and maximum observed values during the monitoring (0 and 22 $\frac{l}{h}$ for the biogas production flow, 10 and 58% for biogas methane content).

2.2.3. Model test cases definition

To test the behavior of the model in a practical context, different scenarios were evaluated varying the location (Lampedusa, in Sicily and Tarvisio, in the Alpine region of Friuli Venezia-Giulia), the presence

Table 4
Summary of the applications scenarios.

Scenario	Location	Insulation	Base heating
1	Lampedusa	No	No
2	Lampedusa	No	Yes
3	Lampedusa	Yes	No
4	Lampedusa	Yes	Yes
5	Tarvisio	No	No
6	Tarvisio	No	Yes
7	Tarvisio	Yes	No
8	Tarvisio	Yes	Yes

of thermal insulation and base heating. The resulting eight scenarios are summarized in Table 4.

The choice of the two locations in Italy was made to represent the climate of two typical regions where access to energy can be limited and, hence, a micro-scale digester could have particular relevance in the local context: the island of Lampedusa, disconnected from the mainland's electricity and gas grids (thus representing some sort of micro grid) and the mountain village of Tarvisio, on the border with Austria on the Alps, where small households or hotels can be disconnected from the main energy grids. The climatic conditions of the two locations are represented in Figs. 6 and 7, respectively. The weather data used in the study (ambient temperature, wind speed, direct solar irradiation, diffuse solar irradiation, global horizontal solar irradiation) were available from the EnergyPlus weather database.

In the case of base heating, it was assumed (as in the case of the experimental part of the study) to use an old solar collector, recovered from previous installations, in order to promote sustainability and reduce costs. In the case of Lampedusa, it was assumed that the solar collector has a single glazing, given the mild climate of the Mediterranean island; in the case of Tarvisio, being located in a relatively cold

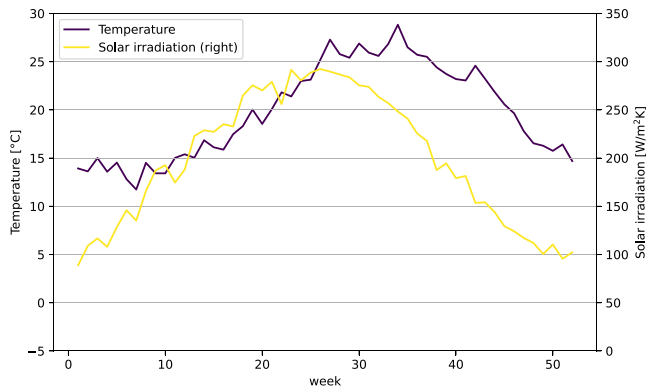


Fig. 6. Summary of climatic conditions in Lampedusa.

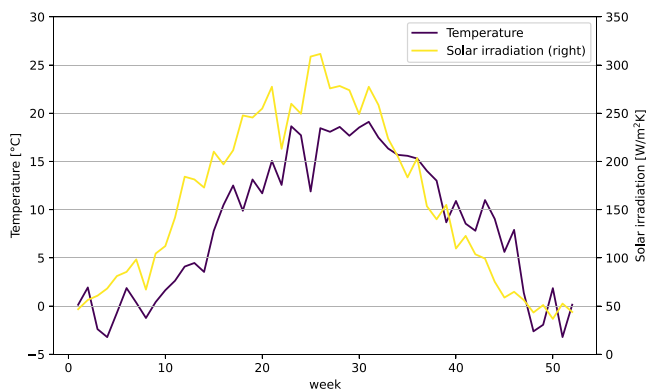


Fig. 7. Summary of climatic conditions in Tarvisio.

Table 5
Parameters describing the solar collectors assumed in the modeling.

Parameter	Single-glazing	Double glazing
Surface	2 m ²	2 m ²
Base efficiency	0.75	0.70
Linear efficiency term	-6.0	-4.0
Tilt	30°	30°
Azimuth	South	South

climate in the Alps, the choice was to use a double-glazing collector. In both cases, the performance of the collector was penalized by 20% with respect to a new one, to account for the fact that they are considered to be used, old panels. The parameters used are summarized in Table 5.

3. Results

This section presents the results obtained from the monitoring of the biodigester production over the observation period (Section 3.1), focusing on the influence of digester temperature on biogas production, and from simulating the proposed digester model in two locations with different climatic conditions (Section 3.2).

3.1. Biogas production monitoring

This section focuses on the experimental part of the paper. More specifically, it presents the analysis of the total productivity during the monitoring period (Section 3.1.1); of the influence of the digester's internal temperature on biogas production (Section 3.1.2) and on biogas methane content (Section 3.1.3); and the analysis of the effect of insulating (Section 3.1.4) and heating (Section 3.1.5) the digester.

3.1.1. Total productivity

Overall, during the monitoring period, the two digesters produced an average of 344 litres of biogas per day (160 l/d for digester 1, 184 l/d for digester 2). As shown in Fig. 8, the generation varies substantially during the year, most of it happening during the summer season. A total of 601 kg of wet mass were added to the digesters, which resulted in a total production of 145 m³ of biogas with an average 53% CH₄ volumetric fraction in the biogas. This corresponds to a conversion efficiency of 84 kg of CH₄ per ton of organic matter supplied to the digesters, a result in line with expected performance from these types of systems [37].

3.1.2. Influence of internal digester temperature on biogas production

The biogas generation shows very similar trends for the two digesters. In both cases, there is a clear correlation between biogas generation and digester temperature. This is shown in Fig. 9: although there are relatively wide variations across the temperature range, showing that other operational conditions also play an important role, the overall trend is clear. The biogas production become negligible (below 5 l/h) at temperatures below 15–18 °C. From 18 °C, the biogas production increases to 10 l/h, with an approximate increase of 1.2 l/h for each 1 °C increase in internal digester temperature. At 39 °C internal digester temperature, the median biogas production was 18 l/h for digester 1 and 25 l/h for digester 2 with an average of 22 l/h each for the combined system.

3.1.3. Influence of internal digester temperature on biogas quality

The availability of measurements of gas compositions allowed also estimating the quality of the biogas generated. As shown in Fig. 10, the results are however somehow inconclusive: the initial tests, performed in the early part of the year 2022, seemed to show that the operating temperature has little to no influence on the CH₄ content of the biogas. The tendency observed in the fall and winter seasons of 2023 showed, instead, a relatively clear trend of decreasing CH₄ content with decreasing temperature. More specifically, the biogas quality was stable above 50% for internal temperatures above 20 °C; between 15 °C and 20 °C we observed a decrease in concentration, and the lowest values of 30% CH₄ concentration in biogas (a value that makes the biogas almost unusable in practical application without further treatment) were observed for temperatures below 15 °C.

3.1.4. Experimental evaluation of the effect of digester thermal insulation

The effects of the thermal insulation applied to the digester 2 at the end of January 2024 are shown in Fig. 11, where the internal and base temperature of the digester, together with the ambient temperature and the solar radiation, are shown for a three-days period before (Fig. 11(a)) and after (Fig. 11(b)) the application of the insulation to digester 2.

The insulation seemed to achieve two main effects, when compared to the non-insulated system: first, it reduced the amplitude of the variation of the internal temperature of the digester, which is a desired effect; second, it caused an overall reduction of the digester internal temperature, which instead is undesirable. This seems to be due to the fact that the insulation layer, as it was designed, reduces the effect of the incoming solar radiation, which during winter provides a significant contribution to the digesters' thermal balance. This is particularly clear when looking at Fig. 11(b), which shows how the temperature increase during sunny days is almost entirely absent in the case of digester 2 after the installation of the insulating layer.

3.1.5. Experimental evaluation of the effect of digester base heating

The impact of heating the digester using the heating plates underneath is shown in Fig. 12. The effect on the base temperature is immediate, while the internal temperature evolves more slowly. At similar ambient conditions, however, the internal temperature seems to further stabilize, and to increase from approximately 14 °C to 16 °C. In general, thanks to the contribution of solar heating, the digester can

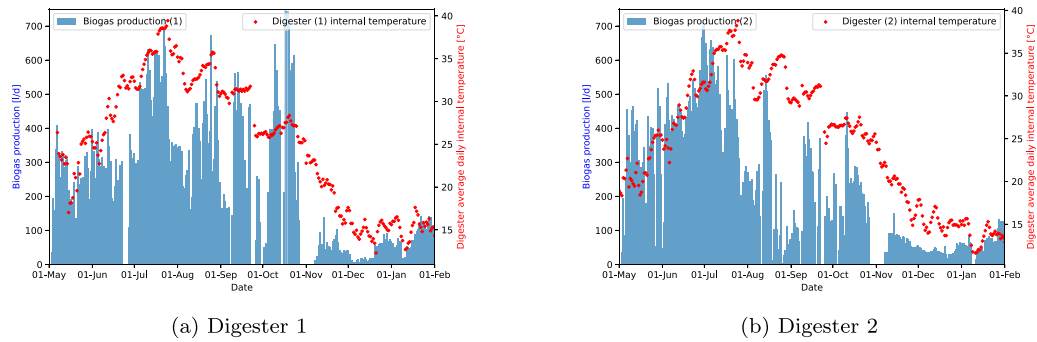


Fig. 8. Total daily biogas generation and average daily internal temperature for the two digesters.

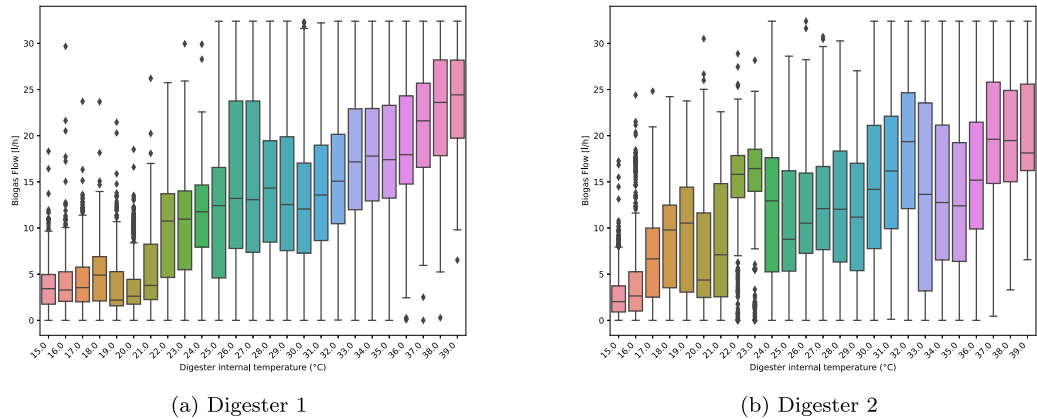


Fig. 9. Boxplot of the biogas production over the course of the monitoring period for different digester internal temperatures.

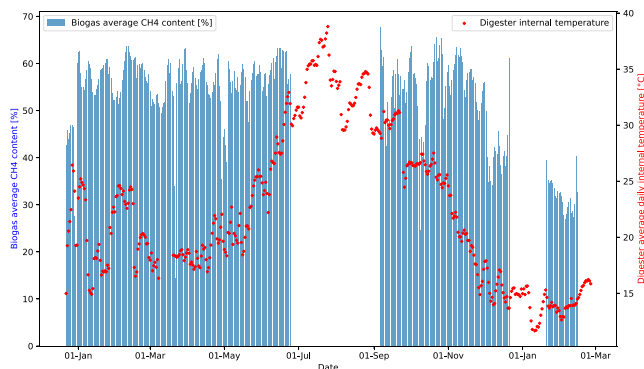


Fig. 10. Average daily CH₄ concentration in the generated biogas and average daily internal temperature. Digester 2.

maintain an average temperature 1.2 °C above the average ambient temperature, while the internal temperature was 0.7 °C below the average ambient temperature in absence of heating.

This also shows the positive influence of the combination of heating and insulation. During the reference period 07-12-2023 to 16-12-2023 the average internal temperature of digester 2 (non-insulated) was only 0.3 °C above the average ambient temperature, 0.9 °C lower than what observed when digester 2 was both heated and insulated.

3.2. Biogas production modeling

The results of the application of the proposed digester modeling to the scenarios are shown in Figs. 13 to 17.

The monthly average internal digester temperature is shown in Fig. 13. These results show that, in the case of Lampedusa, this temperature

is always above 15 °C, suggesting that some biogas production can be expected even during winter. In Tarvisio, on the other hand, the internal digester average temperature is expected to be above 15 °C only between May and September, suggesting that the biogas production could be relevant only during these months.

The analysis of Fig. 13 and Table 6 also allows evaluating the effect of the thermal insulation and of base heating on the yearly performance of the systems. Consistently with the results of the experimental campaign, the results of the simulations show that insulating the digester have limited effect, regardless of the climate, if not associated with other measures. Solar-powered base heating, on the other hand, is always effective, leading to an increase in monthly average temperatures of approximately 0-2 °C depending on the local climate. The results also show that the combination of insulating and heating the digester is the solution that provides the most promising results: the combination of the two measures brings synergic benefits that allow the temperature increase to reach approximately 5.5 °C during summer in Lampedusa and approximately 5.3 °C during summer in Tarvisio.

The monthly average biogas production simulated by the model is shown in Fig. 14 and Table 7. The results show, as expected, that the yearly biogas production is remarkably higher in the mild climate of Lampedusa compared to the relatively cold climate of Tarvisio. Nevertheless, during summer, the biogas digester can be expected to provide a significant contribution even in colder climates.

The comparison of the different scenarios also further highlights the benefits that can be expected from the combined use of thermal insulation and solar base heating. This is particularly true in the case of Tarvisio, where the yearly biogas production is increased by approximately 61% compared to the base case, while the increase in the same scenario in Lampedusa is estimated to be approximately 32%.

The average monthly methane content is shown in Fig. 15 and in Table 8. According to the results, the biogas produced in Lampedusa can be considered to be usable during the whole year, and only during

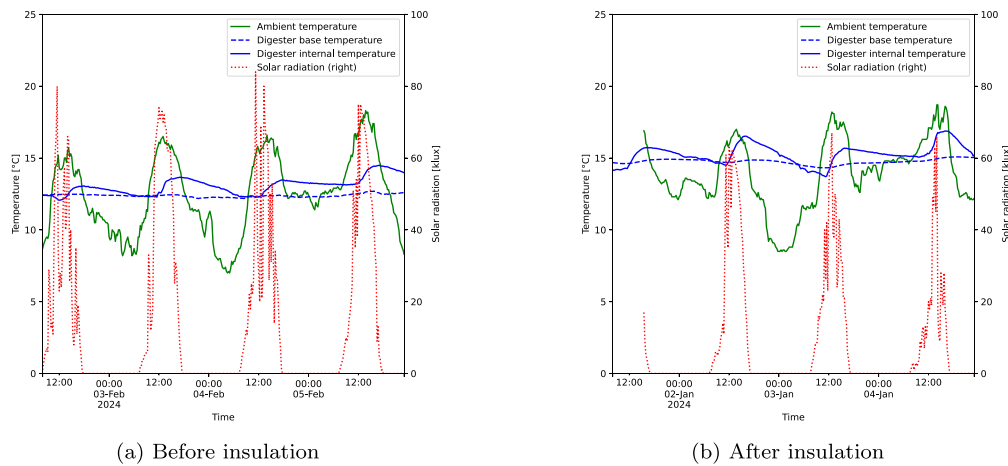


Fig. 11. Temperature evolution in the digester 2 before and after the insulation layer is applied.

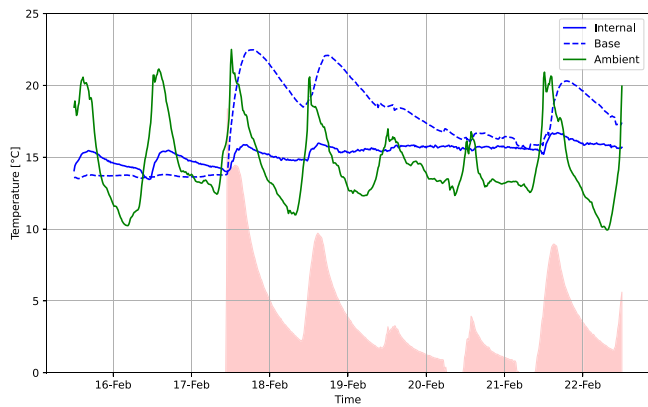


Fig. 12. Temperature evolution in digester 2 (insulated) with and without the contribution of solar heating.

Table 6
Net effect of insulation and base heating on monthly average temperatures, in K.

Location	Lampedusa			Tarvisio		
	INS	HEAT	INS-HEAT	INS	HEAT	INS-HEAT
Jan	-0.27	0.28	0.76	-0.36	0.22	0.24
Feb	-0.09	0.46	1.61	-0.45	0.36	0.6
Mar	-0.1	0.67	2.64	-0.88	0.74	1.31
Apr	-0.32	1.05	3.84	-1.2	1.27	2.59
May	-0.35	1.31	4.94	-0.84	1.64	4.35
Jun	-0.54	1.48	5.2	-0.5	1.78	5.13
Jul	-0.27	1.5	5.55	-0.28	1.69	5.33
Aug	-0.16	1.25	4.79	-0.29	1.51	4.46
Sep	0.32	0.84	3.9	-0.01	1.02	3.22
Oct	0	0.54	2.25	-0.24	0.54	1.55
Nov	0.57	0.26	1.75	0.8	0.3	1.71
Dec	0.25	0.18	1.02	-0.18	0.21	0.42

the months of January and February the average percentage of methane in the biogas falls below 40%. In Tarvisio, instead, the biogas produced has a sufficiently high average methane content only between May and September. In April and October, while the production is not zero, the average methane content is too low (below 30%) to ensure usability.

Finally, the resulting energy in the biogas is shown as the average daily value for each month in Fig. 16 and Table 9. As expected, the differences are magnified across different months as a consequence of the combined effect of both the gas volume and methane content being influenced by the internal temperature.

Looking more in detail at the hourly evolution of the variables of interest, it is possible to get a better understanding of the phenomena

Table 7
Net effect of insulation and base heating on monthly total biogas production, in liters.

Location	Lampedusa			Tarvisio		
	INS	HEAT	INS-HEAT	INS	HEAT	INS-HEAT
Jan	-157	160	435	0	0	0
Feb	-61	229	824	0	0	0
Mar	-59	387	1518	0	0	0
Apr	-180	584	2138	-446	426	754
May	-201	755	2840	-492	936	2492
Jun	-303	825	2893	-276	990	2858
Jul	-154	864	3190	-164	970	3063
Aug	-93	720	2756	-169	867	2563
Sep	178	469	2169	-7	563	1789
Oct	3	308	1294	-172	180	568
Nov	315	146	972	0	0	36
Dec	146	103	586	0	0	0
Total	-565	5550	21,614	-1725	4933	14,122

Table 8
Net effect of insulation and base heating on monthly average methane content in the biogas in %.

Location	Lampedusa			Tarvisio		
	INS	HEAT	INS-HEAT	INS	HEAT	INS-HEAT
Jan	-1.9	1.55	3.06	0	0	0
Feb	-0.18	2.78	8.29	0	0	0
Mar	-0.66	2.3	6.35	0	0	0
Apr	-0.42	1.35	3.21	-6.66	4.22	5.42
May	-0.17	0.48	1.02	-2.91	4.99	9.2
Jun	-0.06	0.12	0.23	0.2	1.87	3.36
Jul	-0.01	0.02	0.05	-0.12	0.45	0.81
Aug	0	0.02	0.04	-0.15	0.54	0.98
Sep	0.01	0.03	0.08	0.09	2.36	5.21
Oct	0	0.05	0.16	-0.65	5.57	15.26
Nov	0.31	0.14	0.75	-0.03	0.21	1.67
Dec	0.65	0.49	2.36	0	0	0

involved in the process. Fig. 17(a) shows the evolution of the internal digester temperatures over a reference 4-days period in February. Compared to the base case, solar base heating magnifies the heating effect from solar radiation, providing a small but consistent improvement in the internal temperature.

The thermal insulation, on the other hand, provides an improvement when solar radiation is low, but causes temperatures to be lower than the reference case when solar radiation is higher, due to the fact that it prevents direct digester solar heating to work effectively. This is particularly evident in the case of Tarvisio in April (Fig. 17(b)), where the temperature of the insulated digester is always lower compared to all other scenarios.

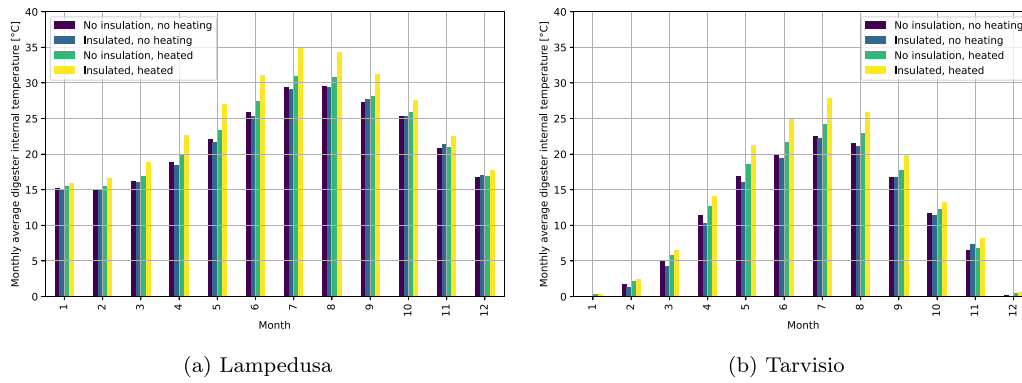


Fig. 13. Comparison of monthly average digester temperature across scenarios.

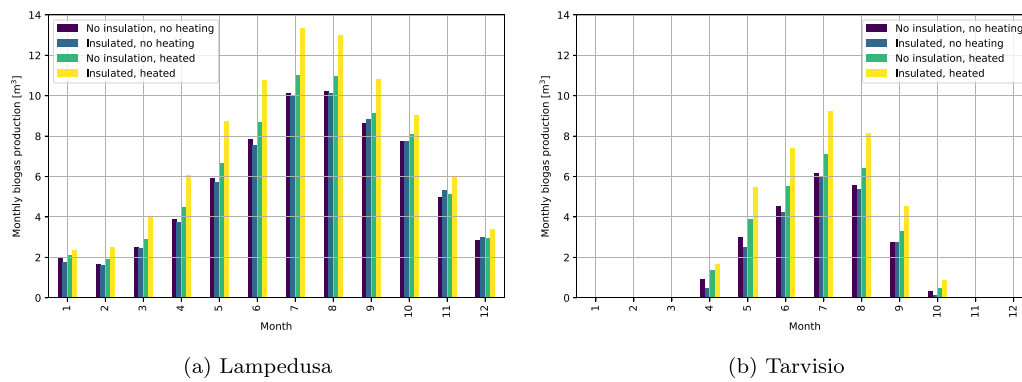


Fig. 14. Comparison of monthly biogas production across scenarios.

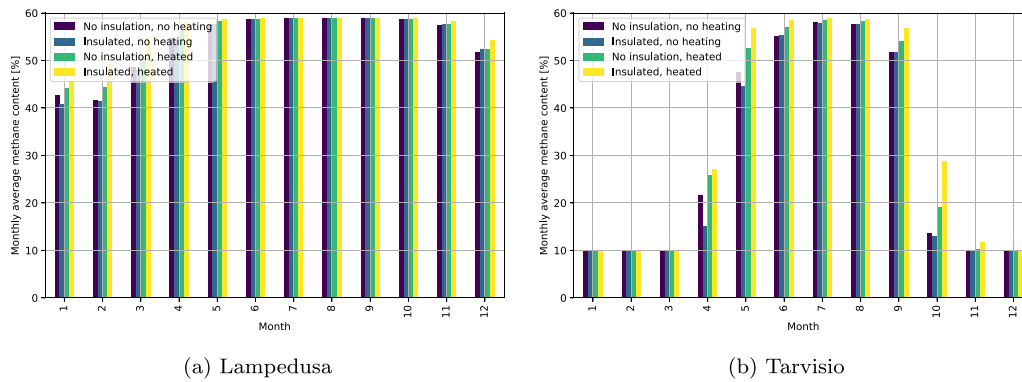


Fig. 15. Comparison of monthly average biogas methane content across scenarios.

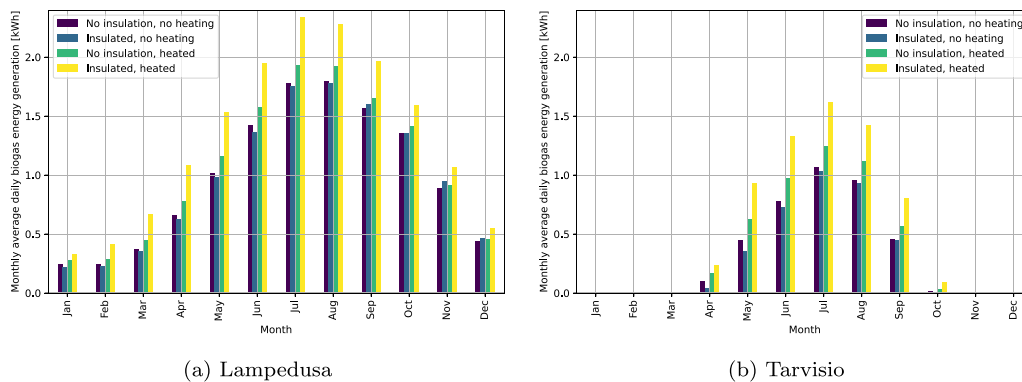


Fig. 16. Comparison of monthly average of daily energy content in the biogas produced across scenarios, in kWh.

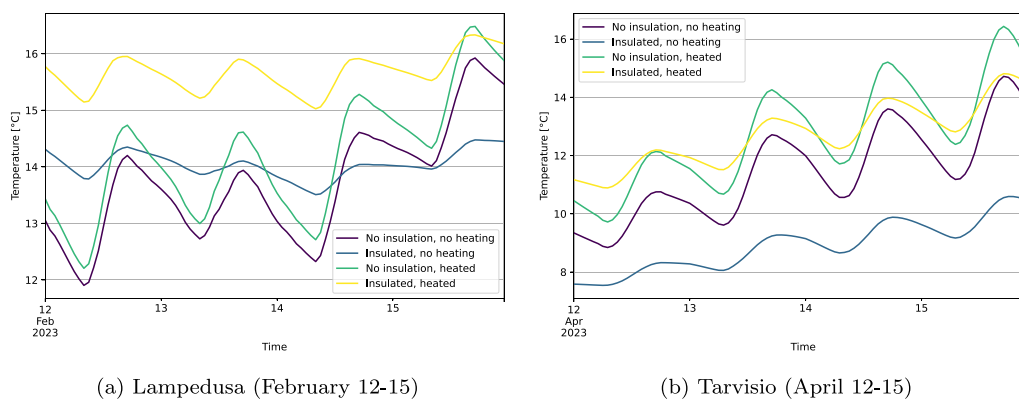


Fig. 17. Comparison of internal digester temperature across different scenarios.

Table 9
Monthly average daily energy content in biogas, in kWh/d.

Location variable	Lampedusa				Tarvisio			
	Base	INS	HEAT	INS-HEAT	base	INS	HEAT	INS-HEAT
Jan	0.24	0.22	0.27	0.33	0	0	0	0
Feb	0.24	0.23	0.29	0.41	0	0	0	0
Mar	0.37	0.35	0.44	0.66	0	0	0	0
Apr	0.66	0.62	0.78	1.08	0.09	0.04	0.17	0.23
May	1.02	0.98	1.16	1.53	0.44	0.35	0.63	0.93
Jun	1.42	1.36	1.57	1.95	0.78	0.73	0.97	1.33
Jul	1.78	1.75	1.93	2.34	1.06	1.03	1.24	1.61
Aug	1.79	1.78	1.92	2.28	0.96	0.93	1.12	1.42
Sep	1.57	1.6	1.65	1.96	0.45	0.45	0.56	0.8
Oct	1.36	1.36	1.41	1.59	0.01	0	0.03	0.09
Nov	0.88	0.94	0.91	1.07	0	0	0	0
Dec	0.44	0.47	0.46	0.55	0	0	0	0

The combination of base heating and thermal insulation provides higher temperatures almost at all time steps, with the exception of periods when the contribution of the solar collector is low, due its dependency on the collectors' efficiency, which decreases with low ambient temperatures.

4. Discussion

This section provides additional insight into the work presented in this paper. Section 4.1 discusses the results and their relevance; Section 4.2 examines the methodological choices and their potential influence on the outcomes; finally, Section 4.3 outlines suggestions for future research in the field.

4.1. Results discussion

The effect of the internal temperature on the biogas production confirms what is considered common knowledge for biogas production facilities, regardless of the size. Given the range of operating temperatures observed during the monitoring period, the tendency showed a general and monotonic increase of the biogas production rate with temperature.

The effect of the internal digester temperature on the methane fraction in the biogas was less clear and requires further investigation. One possible explanation is that long periods at relatively low temperatures, rather than low temperatures themselves, could be the cause of a drop in CH₄ concentration. This phenomenon was observed by visual examination of the results of the long-term monitoring of the experimental facilities, but also confirmed by the model calibration, that converged to a value of 6.9 for the number of past days to calculate the average temperature to use in the correlation to estimate biogas methane content. In general, maintaining the internal temperature

above 20 °C seemed to be the threshold for a sufficient biogas production, both in terms of quality and quantity. In general, we obtained biogas with a methane content in line with what reported by other authors working with non-temperature controlled digesters, such as Twizerimana et al. [45].

The work also attempted to estimate the impact of different strategies to increase the digester's internal temperature. Applying a thermal insulation layer to the digester did not achieve the desired results: while allowing to stabilize the temperature, the overall effect on the average temperature was negative, as limiting conduction and convection losses was more than compensated by the reduced radiative contribution. This result was observed experimentally and verified as a result of the modeling of the system. In the authors' view, these results represent a valuable contribution to the existing literature, which is currently limited on this specific topic. Weatherford and Zhai [69] reported a very high positive effect of digester insulation on internal temperatures, but only looked into the insulation of the bottom and sides of the trench where the digester was placed, a situation which is very different from above-ground installations; Twizerimana et al. [45] found a positive effect when placing a lab-scale digester in sawdust, but these results were obtained in a closed environment, with no contribution from solar radiation.

The use of an external, solar-powered heater (both stand-alone and together with thermal insulation of the digester) showed positive results, even when using old solar collectors with low efficiency. More specifically, an increase in biogas production volume of 32% and 61% was observed, depending on the location. These results confirm what reported in existing literature on the subject, that show a positive effect very variable depending on the location and on the specifics of the digester. Makamure et al. [70], for instance, found a 33% biogas volume increase when using thermal solar panels in combination with an internal heat exchanger; Quinto et al. [71] obtained a 16.6% increase in production for a lab-scale digester in Mexico City. El-Wahab et al. [72] found that the increase could reach up to 129% when testing a similar system in Egypt.

4.2. Methods discussion

From an experimental perspective, the absence of monitoring and control of the digester organic feed introduces an element of uncertainty in the analysis of the biogas production. The relations derived for biogas generation as a function of temperature are based on the assumption that the digester was fed regularly and using biomass that can be considered as representative of typical conditions. Real conditions clearly differ from each case of application, and further work could focus on the influence of different kind of deviations from standard operational conditions (e.g. not feeding the digester for long consecutive days, etc.). For what concerns the type of feed, while acknowledging the limitation of the proposed approach, it should be

noted that even having information on the composition of the organic fraction (carbohydrates, proteins, lipids) would not provide clear indications regarding biogas production effects, according to existing literature in the field [62,63].

More generally, the choice between a realistic, uncontrolled setting (the approach chosen for this study, but also by e.g. [61,70]) and a controlled setup in a laboratory environment (e.g. [45,60]) has consequences on the validity of the results. In this work, it was preferred to adopt a more empirical approach, since the main objective of the study was to include these systems in larger, system-wide models to model, simulate and optimize residential-scale energy systems including biogas as one of the available energy sources. This choice, however, reduces the experimental stability and the possibility of getting a more accurate understanding of the underlying phenomena.

From the perspective of the digester modeling, it is part of every modeler's work to select a model that fits the specific case. Even the simplest models that are commonly used for anaerobic digesters, such as the ADM1, require the prior knowledge of a set of parameters relative to the specific digester model, as well as requiring knowledge of the composition of the biomass input. These features do not fit well with studies whose main objective is to include the digester in a larger system. We believe that the model proposed in this paper represents the appropriate trade-off between model complexity and accuracy for such studies.

The thermal model of the digester was also simplified, to reduce the computational burden and avoid including further unknown parameters in the model. Some of the modeling choices can be challenged: for instance, the assumption of using one single control volume for the whole digester; or the choice of not considering a dedicated heat exchange surface with the ground. These choices will be the subject of further investigation in future research on the topic.

The proposed model was validated based on data collected from one single digester, in one specific location. While it is common practice in academic literature on the subject to only have one facility to experiment on (see, for instance, [61,69]), the proposed modeling approach could be strengthened by extending the validation to additional experimental data, both from the same facility and, especially, from another located in different climatic conditions.

4.3. Future work

The results of both the experimental and the modeling parts of this study allowed addressing the research gap originally identified but also raised new questions that require further work to be clarified.

From the experimental point of view, future work should focus on extending the experimental campaign with the chosen digester technology to other locations with different climatic and operating conditions. This would allow increasing the understanding of the system's performance, improving the modeling approach and better validating it.

Further work should also focus on a comparison between the proposed model and more traditional approaches, such as the ADM1, to better understand its strengths and limitations when compared to what is currently considered state-of-the-art on the subject.

This study investigates the effect of two solutions for increasing the digester's internal temperature and, thus, its productivity: external insulation, and heating through a heating plate. Further work should focus on applying the proposed methodology (thus combining an experimental and a modeling approach) to other alternative solutions: based on existing literature, both the use of direct electric heating using photovoltaic panels [73] and especially that of greenhouses [43, 48,49] can be beneficial, and the applicability of these solutions to temperate climates in developed countries is considered worth further investigation.

The results of this study showed a positive contribution from heating the digester using solar collectors, both as a stand-alone solution and

in combination with thermal insulation. However, solar collectors could also be directly used for domestic hot water generation. The comparison of the advantages and disadvantages of using solar collectors for digester heating, compared to their direct use for hot water generation, should be further investigated to avoid investing in sub-optimal system configurations.

More generally, further work could focus on using the proposed model for estimating different configurations of polygeneration systems, including micro-scale anaerobic digesters but also other local generators, to analyze the technical, economic and environmental trade-offs between alternative designs. This would also allow performing a full cost-benefit analysis to compare the additional investment cost and operational complexity of such systems to their expected benefits.

5. Conclusion

In this paper, biogas production from a micro-scale plant was monitored for 12 months of real-life operations, with the aim of understanding the actual potential for biogas generation and investigate possible challenges arising from everyday use.

The results of the experimental part of the study showed that, depending on the climatic conditions of the selected location, the micro-digester can provide a significant contribution to the energy balance of a system, especially in warm climates and during summer and mid-season, due to the high influence of the internal temperature on both the biogas production and on its methane content. During the monitoring period, the two digesters that were part of the experimental campaign produced an average of 160 and 184 liters of biogas per day, leading to a total production of approximately 145 m³ with an average methane content in the biogas of approximately 53%.

The data collected during the monitoring phase were used to propose and calibrate a complete model of the digester, that allows simulating its internal temperature based on external meteorological conditions and, from that, the production quantity and quality of biogas. The proposed model, once calibrated, was applied to two locations with different climates in Italy (the Mediterranean island of Lampedusa and the alpine village of Tarvisio). The application of the model allowed estimating the expected production and evaluating the potential benefits from two solutions that had been tested experimentally to improve biogas production: adding a thermal insulation layer around the digester, and heating the digester using a base heat exchanger receiving heat from a solar collector.

The results of the simulations, in agreement with what observed experimentally, showed that the thermal insulation of the digester is only beneficial when associated with solar heating, while if applied alone it reduces the digester's performance (−0.1% average internal temperature and −0.2% yearly energy generation in Lampedusa, −3.3% and −6.9% in Tarvisio). While solar heating alone brings some useful benefits, the results showed that the combined heating and insulation of the digester is the most interesting solution, especially in colder climates (+14.6% average internal temperature and +33.7% yearly energy generation in Lampedusa, +22.9% and +69.0% in Tarvisio).

CRedit authorship contribution statement

Francesco Baldi: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis. **Paolo Sdringola**: Writing – review & editing, Writing – original draft, Conceptualization. **Simone Beozzo**: Software, Investigation, Data curation. **Biagio Di Pietra**: Supervision, Resources, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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This paper is an extension of the study “Experimental evaluation of a microscale biogas reactor for household waste-to-biogas conversion” presented in Rome (Italy) on the 11th of September 2024 at the 19th Conference on Sustainable Development of Energy, Water and Environment Systems (SDEWES).

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