Hybridization of anaerobic digestion with solar energy: A solution for isolated livestock farms

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ABSTRACT

Intensive farming causes an important amount of greenhouse gas emissions. This scenario can be significantly reduced by the implementation of renewable technologies and transforming farms from energy consumers to energy providers. In the particular case of livestock production, biogas and solar energy reduce greenhouse gas emissions and the energy demand of the installations. However, the implementation of these technologies requires solutions adapted to local scenarios, such as connectivity to the energy grids. In this work, a biogas/biomethane production system, energetically covered with hybrid solar panels is proposed as a solution for isolated areas where biodegradable substrates (manure) are abundant. Thus, the electrical and thermal requirements of the digester are supplied by solar panels, reducing the biogas self-consumption and the energy inputs from the electrical grid. Hybrid solar panels also provide sufficient energy for operation of an upgrading system to obtain biomethane of fuel vehicle quality, increasing the energy self-sufficiency of the agricultural activities. This solution has been simulated in five different climatic regions corresponding to areas of intense pig farming activity. The results demonstrate the sustainable bioenergy production in isolated farms with limited connection to the energy grid and organic matter availability. Furthermore, the economic study showed that the proposed technology is competitive compared to other technologies in the energy sector.

1. Introduction

Primary sector is a significant contributor to the greenhouse gas emissions (GHG) [1]. According to the last estimations, more than 50% of GHG emissions in 2050 will be produced by activities related to agriculture, livestock production, forestry or mining. As a consequence of the sector characteristics, the mitigation of GHG emission is difficult and the alternatives should focus on transformation towards a double perspective [2]. On the one hand, focusing the sector as a producer and not only as an energy consumer, and on the other hand, substituting the fossil fuels used in the process for renewable energies. This strategy requires the connection of the energy sector with the primary sector by the implementation of renewable technologies that reduce greenhouse gas emissions and energy prices [3,4].

Agriculture, livestock production and forestry activities produce a large number of renewable feedstocks as by-products (manure, straw, sawdust among others). Introducing these materials into the energy production sector would ensure sustainability and connect agriculture with other economic sectors [5,6]. In this context, anaerobic digestion of organic wastes produced in intensive farming offers multiple advantages (e.g. biogas is produced under controlled conditions to replace consumption fossil fuels) [7,8], while liquid digestate is generated as a value-added product for crop fertilization and soil amendment [9,10]. In addition, the process also avoids the release of methane emission from storage wastes, which has a warming effect considerably more harmful than CO_2 on a 100-year time frame [11].

This transformation of the primary sector involves an integration into the energy production system, which requires novel solutions able to respond to the increasing energy needs of the society and the replacement of oil and natural gas. The solutions must ensure energy supply without prohibitive installation costs or undue consumption of

Nomenclature

C_{fa}	Humid subtropical climates (temperate, no dry season, hot summer)	K	Heat transfer coefficient (W m^{-2} °C^{-1})
		LCOE	Levelised cost of energy (USD kWh^{-1})
C_{fb}	Oceanic climates (temperate, no dry season, warm summer)	M_t	Operations and maintenance expenditures in the year t (USD)
C_{sb}	Mediterranean warm/cool summer climates (temperate, dry summer, warm summer)	ηb	Biogas yield (m^{-3} kgVS^{-1})
		η_{bo}	Boiler efficiency (%)
D_{fa}	Hot summer continental climates (continental; no dry season, hot summer)	η_e	Thermal conversion efficiency (%)
		η_{pv}	Photoelectric conversion efficiency (%)
D_{wa}	Hot summer continental climates (continental, dry winter, hot summer)	ηts	Thermal system efficiency (%)
		η_{es}	Electricity system efficiency (%)
d	Density (kg m^{-3})	n	Lifetime (y)
E	Energy (kWh)	Q	Substrate flow rate (m^3/d)
E_t	Electricity generation in the year t (kWh)	r	Discount rate (%)
H	Heat (kWh)	TS	Total solids (g kg^{-1})
HRT	Hydraulic Retention Time (d)	upgrading$_{hc}$	Heat required to upgrade 1 m^3 of biogas to biomethane (kWh)
I_t	Investment expenditures in the year t (USD)	VS	Volatile solids (g kg^{-1})
		WT	Working time (h)

resources (energetic or not). In this sense, decentralised energy production systems provide opportunities for resources exploitation locally, together with energy self-sufficiency in remote communities [12]. When biogas in produced on farm, decentralization is particularly necessary since residual feedstock used as substrate in anaerobic digestion are normally produced far from energy grid connections (electrical or gas pipelines). That is the case of livestock farms (piggery, cattle and poultry), which are clearly underutilised for biogas generation [13]. The decentralization strategy will require new digester configurations able to operate with minimum operational costs in areas with limited energy connectivity, where the organic substrates are produced. Hybridization of digester with solar energy sources has been proposed as solution to widespread biogas production into diverse locations, including remote and off-grid areas [14]. Proposed solutions that combine digesters and solar collectors would increase the overall efficiency of each technology and reduce reliance on carbon-based energy sources, contributing to a

more sustainable and environmentally friendly solution [15,16]. Other systems combining digesters and other renewable sources, such as wind power, have been proposed by means of microgrids and hydrogen production systems, resulting a complex integration difficult to implement at this scale [17–19]. In this sense, solar panels, that generate electricity and/or thermal energy, in a very wide range of scale, can provide the energy requirements of anaerobic digesters, increasing the efficiency of the biogas production process [20–22].

In this work, a novel hybrid technology is proposed for biogas and biomethane generation in isolated farms with limited connectivity to electrical and gas grid. Hybrid solar panels, that simultaneously produce heat and electricity, provide the thermal energy required for an optimised anaerobic fermentation (between 35 and 55 °C) and electricity for mixing and pumping. Since, energy surpluses, in form of heat and electricity, are produced by solar hybrid panels, biogas transformation into biomethane using a conventional upgrading technology can be also
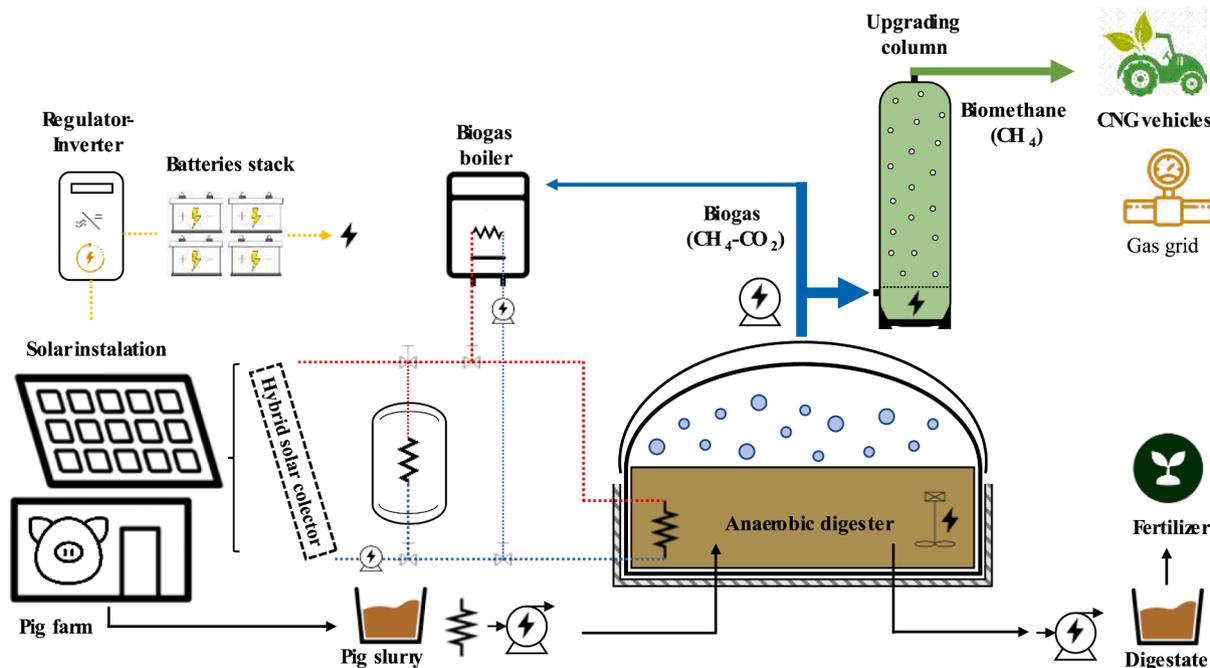

Fig. 1. Schematic diagram of the Anaerobic digestion/Solar (AD/S) system studied. Legend: Colour lines: Black-liquid substrate; Blue-Biogas; Green-Biomethane; Yellow-Electricity line; Red and blue dotted line-Thermal hydraulic line.

energetically supported. The study develops the field of hybridization of solar energy with anaerobic digestion by focusing on a critical and less explored aspect: harnessing solar energy generated by hybrid collectors to meet the energy (electrical and thermal) demand of the digester up to the stage of biomethane generation. Previous studies in this field have mainly focused on the thermal demand, using solar water heaters for temperature exchange or greenhouses [15,16,23]. Other proposals include hybrid polygeneration energy systems in rural communities involving micro-grids and multiple energy sources [20,21]. In the technology herein presented, the energy demand for biogas generation and its further transformation into biomethane is covered by solar energy. A complete study of an anaerobic digester coupled to biomethane production supported with sunlight is presented. Swine manure was herein considered as a model substrate given the widespread distribution around the globe and the isolated configuration of these facilities [24]. Five locations, chosen for representing areas with high levels of pig farming, were simulated to assess the energy sufficiency and the exportation of energy as biomethane for its final use as biofuel. Finally, an economic analysis has been conducted considering the capital and operational costs of integrating the anaerobic system with solar panels. This analysis was then compared in terms of levelised cost of energy (LCOE), serving as a metric for the net average current cost of energy generation throughout the lifecycle of the system and a normalize value for comparison with other technologies.

2. Materials and methods

2.1. Hybrid system description

The hybrid system proposed is presented in Fig. 1. A set of Photovoltaic/Thermal (PV/T) hybrid solar collectors connected to a battery stack and a thermal energy storage tank provides the energy requirements of a conventional anaerobic digester. The biogas produced is then directed to an upgrading system to generate biomethane. A chemical absorption system was chosen to eliminate CO_2 and other undesirable elements, since thermal energy and electricity are consumed along the upgrading process.

A medium size pig farm with 2000 heads was herein used as model farm [25,26]. A conventional cylindrical digester of 9 m diameter and 4.5 m height was considered for biogas generation from the liquid waste of the farm. The digester is operated at a hydraulic residence time (HRT) of 25 days. The volume of the digester was calculated using Eq. (1):

$$Digester\ volume\ (m^3) = \frac{substrate\ V}{day}\left(\frac{m^3}{day}\right) * HRT\ (days) * 1.3(biogas\ factor)$$

(1)

Where the substrate V is the volume introduced per day in the reactor, HRT is the hydraulic retention time, and the biogas factor is included to account for the headspace of the digester.

Pig slurry substrate presents fluctuations in composition, especially in organic matter content, which depends in turn on growth stage, animal diet and seasonality. Representative average characteristics have been used in these calculations [27,28].

A commercial PV/T hybrid module was considered for this simulation. The maximum temperature of the panel collector was set at 80 °C, with a set point between 30 and 40 °C inside of the anaerobic reactor, i. e., a biogas boiler was also included in the simulation for periods with insufficient solar radiation.

The electricity produced by the solar modules is connected into a combiner box equipped with batteries. The electricity is then used to operate the digester, pumps, mixers or in the biogas upgrading unit. During periods of low irradiation levels, the upgrading process is stopped given priority to the digester operation.

The heat captured by the module field is stored into a tank and a thermal exchanger is utilised to increase the temperature of the digester

Table 1
Characteristics of the proposed system.

Parameter	Value	References
Anaerobic digester		
Working volume (m³)	700	(Ahlberg-Eliasson et al., 2017)
Working temperature (°C)	35	
HRT: Hydraulic Retention Time (d)	25	
Substrate: Pig slurry		
Managed volume (m³ y⁻¹)	11,500	(Dieter Deublein & Angelika Steinhauser, 2011; Marchetti et al., 2022; Ning et al., 2019; Santos et al., 2022)
Moisture content (%)	95	
Density (kg m⁻³)	≈1	
TS: Total Solids (g kg⁻¹)	45.3	
VS: Volatile Solids (g kg⁻¹)	33.3	
ηb: Biogas yield (m³ kgVS⁻¹)	0.5	
Biogas upgrading technology: Chemical absorption		
Energy consumption	0.1–0.15 kWh m⁻³ and 0.5–0.75 kWh m⁻³ (heat) raw gas	(Abdeen et al., 2016; Ward et al., 2021)
Efficiency (%)	96.7–97.7	
Solar system: Hybrid technology		
ηe thermal conversion efficiency (%)	60	Commercial hybrid solar collector
ηpv photoelectric conversion efficiency (%)	17	

until the mesophilic conditions (35 °C) [29]. This equipment operates by facilitating heat transfer between a network of tubes, allowing the hot fluid from solar panels and the cold fluid from within the anaerobic digester to circulate. As these fluids flow in proximity, heat transfer takes place [30]. According to the calculations, 200 m² of hybrid solar collectors are necessary to cover the energy requirements of the digester and the upgrading unit, which corresponds to a minor portion of the roof surface of the farm facility house. Considering the average size of these installations, between 1000 and 2000 m² in case of 2000-head pig farm, the surface covered by panels range between 5 and 10 % of the farm roof [33]. Average efficiencies of 60% and 17% for thermal and electrical energy were assumed in this calculation. These values are in range of the commercially available hybrid panels.

A heat exchanger with a total surface of 2 m² was herein used by considering the most adverse thermal conditions of the year according to Eq. (2):

$$Q = U_{ex} * A_{ex} * LMTD$$

(2)

Where Q is the heat transferred by the heat exchanger in the worst conditions (between 88.7 and 160.5 kWh depending on the location), U_{ex} is the Heat transmittance of the heat exchanger (1.15 kW m⁻² °C⁻¹, A_{ex} is the exchanger area (m²) and LMTD is a logarithmic mean temperature difference (40–60 °C) [34,35].

The main system characteristics can be seen in Table 1.

The chosen method for upgrading involves a chemical absorption system that utilizes a chemical solvent to absorb carbon dioxide [31]. This process is well adapted to the hybrid system herein presented since both thermal and electrical energy are required. In this sense, average values of energy demand of the upgrading system have been considered: 0.125 kWh and 0.625 kWh of thermal and electrical per m³ of biogas treated respectively, with an average of efficiency energy utilization of 97.3% [32].

Table 2
Electrical equipment, power and working time per day.

	Electricity consumtion		
	Power (kW)	Working time (h)	Energy (kWh)
Pump 1 (digester feeding)	1.1	2	2.2
Pump 2 (digestate extraction)	1.1	2	2.2
Liquid shaker	1.7	12	10.2
Liquid shaker 2	1.7	3	5.1
Liquid pump (heating)	0.75	6	4.5
Liquid pump 2 (heating)	0.75	6	4.5
Gas compressor	0.8	12	9.6
Up-grading unit	0.125 kWh/m³ biogas		

Table 3
Regions selected for the study.

	Soria (Spain)	Iowa (USA)	Odense (Denmark)	Santa Catarina (Brazil)	Laixi (China)
Latitude and longitude	41.7, −2.4	41.6, −91.7	55.3, 10.3	−26.9, −51.7	36.9, 120.5
Köppen climate classification	Csb	Dfa	Cfb	Cfa	Dwa
Annual irradiation (kWh/m²)	1618.7	1492.0	1023.1	1760.0	1477.3
Average annual temperature (°C)	11.4	10.1	9.1	16.7	13.0
Optimum inclination angle (°)	36	37	40	26	33

2.3. Calculations procedure: energy balance

The energy balance considered the energy consumption and generation during the process as heat and electricity, according to Eq. (3)–(4). Biomethane production and the biogas produced were estimated with Eq. (5)–(6). The amount of thermal energy needed for the digester was determined based on the heat necessary to maintain the liquid inside the reactor and the substrate input at a temperature of 35 °C. Thermal needs of the upgrading process were also introduced in this calculation using Eq. (7)–(9). Similarly, the electricity consumption resulted from the operation of the mixers and pumping, as well as biogas upgrading, was estimated with Eq. (10). Finally, thermal energy and electricity production are considered with Eq. (11)–(12)

$$E_{Heat\ Balance}\left(\frac{W \bullet h}{d}\right) = E_{H\ prod} - \left[E_{H\ digester\ demand} \right. \tag{3}$$
$$\left. + E_{H\ substrate\ demand} + E_{H\ upgrading\ demand}\right]$$

Where E is energy and H is heat.

$$E_{Electricity\ Balance}\left(\frac{W \bullet h}{d}\right) = E_{E\ prod} - E_{E\ demand} \tag{4}$$

$$Biomethane_{upgraded} = Biogas_{produced} - Biogas_{used\ in\ the\ boiler} \tag{5}$$

$$Biogas_{produced}\left(\frac{m^3}{d}\right)$$
$$= Q\left(\frac{substrate\ m^3}{day}\right) * d\left(\frac{Tn}{m^3}\right) * TS(\%) * VS(\%) * \eta_B\left(\frac{m^3\ biogas}{Tn_{VS}}\right) \tag{6}$$

$$E_{Heat\ substrate\ demand}\left(\frac{W \cdot h}{d}\right) = Q\left(\frac{substrate\ m^3}{day}\right) * \left(\frac{4.2\ MJ}{°C \cdot m^3}\right) * \Delta(T_{reactor} \tag{8}$$
$$- T_{subst})(°C) * \frac{1}{\eta_{ex}(\%)}$$

Where $\frac{4.2\ MJ}{°C \cdot m^3}$ is the water specific heat (the pig slurry has a 95% water content) and ΔT is the temperature difference between the reactor and the substrate.

$$E_{Heat\ upgrading\ demand}\left(\frac{W \bullet h}{d}\right)$$
$$= \left(Biogas_{produced} - Biogas_{used\ in\ the\ boiler}\right)\left(\frac{m^3}{d}\right) * upgrading_{hc}\left(\frac{Wh}{m^3}\right) \tag{9}$$

Where $upgrading_{hc}$ is the heat required to upgrade 1 m³ of biogas to biomethane.

$$E_{electricitydemand}\left(\frac{W \bullet h}{d}\right) = \sum EP(W) * WT\left(\frac{h}{d}\right)$$
$$+ \left(Biogas_{produced} - Biogas_{usedinthebioler}\right)\left(\frac{m^3}{d}\right) * upgrading_{ec}\left(\frac{Wh}{m^3}\right) \tag{10}$$

Where EP is the equipment power (pumps, mixer) WT is the working time per day and $upgrading_{ec}$ is the electricity required to upgrade 1 m³ of biogas to biomethane (see Table 2).

$$E_{Heat\ prod}\left(\frac{W \bullet h}{d}\right) = \left[Irradiation\left(\frac{kWh}{m^2}\right) * solar\ panel_{surface}\left(m^2\right) * \eta_e(\%) * \eta_{ts}(\%)\right] + \left[biogas_{used\ in\ the\ boiler} * \eta_{bo}\right] \tag{11}$$

Where Q is the substrate flow rate, d is the substrate density, TS and VS are the total and volatile solids of the substrate and η_b is the biogas yield of the substrate.

$$E_{Heat\ digester\ demand}\left(\frac{W \cdot h}{d}\right) = K\left(\frac{W}{m^2 \cdot °C}\right) * A\left(m^2\right) * \Delta(T_{ext} \tag{7}$$
$$- T_{int})(°C) * \frac{24h}{day} * \frac{1}{\eta_{ex}(\%)}$$

Where K is the heat transfer coefficient (0.3 for the digester wall and floor and 1.0 for the cover), A is the area in contact between the inside and outside reactor, ΔT is the temperature difference between the internal (35 °C) and external part of the reactor and ηex is the heat exchanger efficiency (90%).

Where η_e is the solar panel thermal efficiency (%), η_{ts} is the thermal system efficiency taking into account different possible thermal losses (operational issues…) and η_{bo} is the boiler efficiency (90%).

$$E_{electricity\ prod}\left(\frac{W \bullet h}{d}\right)$$
$$= Solar_{Irradiation}\left(\frac{kWh}{m^2}\right) * Solar\ panel_{surface}\left(m^2\right) * \eta_{pv}(\%) * \eta_{es}(\%) \tag{12}$$

Where η_{pv} is the photoelectric conversion efficiency (%), and η_{es} is the electricity system efficiency taking into account different possible electricity losses (15%).

2.4. Study localizations

To assess the robustness of the hybrid AD/S system, it was tested

Table 4
Investment costs of the hybrid PV/T solar system equipment's.

	Equipment	Cost (USD)	Units
Hybrid PV/TSolar System	Solar collector	591	100
	Inverter-Charger	3715	3
	Regulator MPTT	2100	3
	Battery stack	1295	14
	Liquid pumps	4545	2
	Storage tank	2727	2
	Structure, cable, valves, connections, others	1	40%
	Installation	1	20%

under varied climatic conditions. For this purpose, five regions were selected: Soria (Spain), Iowa (United States), Odense (Denmark), Santa Catarina (Brazil) and Laixi (China). All of them represent regions with high density of swine production [36].

The climatological data for each region was studied considering a standard year using Solargis software. The main characteristics of the locations are presented in Table 3. Solar irradiation values and ambient air temperature were used for the calculation of the energy productivity in the panels and the digester requirements. Simulation of the ideal tilt angle for the solar panels was also conducted for each region. Köppen Climate classification has also been included taking account the seasonal precipitation and level of heat [37].

2.5. Economic analysis

Renewable energy resources must be compared among then and with the non-renewable ones in terms of costs of generation. In this scenario a value of levelised cost of energy (LCOE) value is desired. This cost metric has become a standard for assessing and comparing energy technologies and guiding design advancements [38]. Traditionally, LCOE is defined as the annualised costs relative to the annual energy production, represented by Eq. (13) [39].

The computation of LCOE values relies on the total installed costs and specific capacity factors of individual projects, along with the operation and maintenance (O&M) expenses.

$$LCOE = \frac{Generation\ Annual\ Costs}{Annual\ Energy\ Production} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (13)$$

Where I_t the investment expenditures in the year t, M_t operations and maintenance expenditures in the year t, E_t electricity generation in the year t, r the discount rate – 5% according to Weinand et al. [40] - and n the lifetime of the system.

The study focuses on examining the potential rise in biomethane savings resulting from the introduction of hybrid solar equipment into an isolated anaerobic system with 20 years of lifetime to calculate the LCOE. The total investment cost is estimated by considering specific expenses associated with solar collectors, inverter-chargers, Maximum Power Point Tracker (MPPT) regulators, storage systems, and other installation-related items, as shown in the Table 4. O&M costs have been
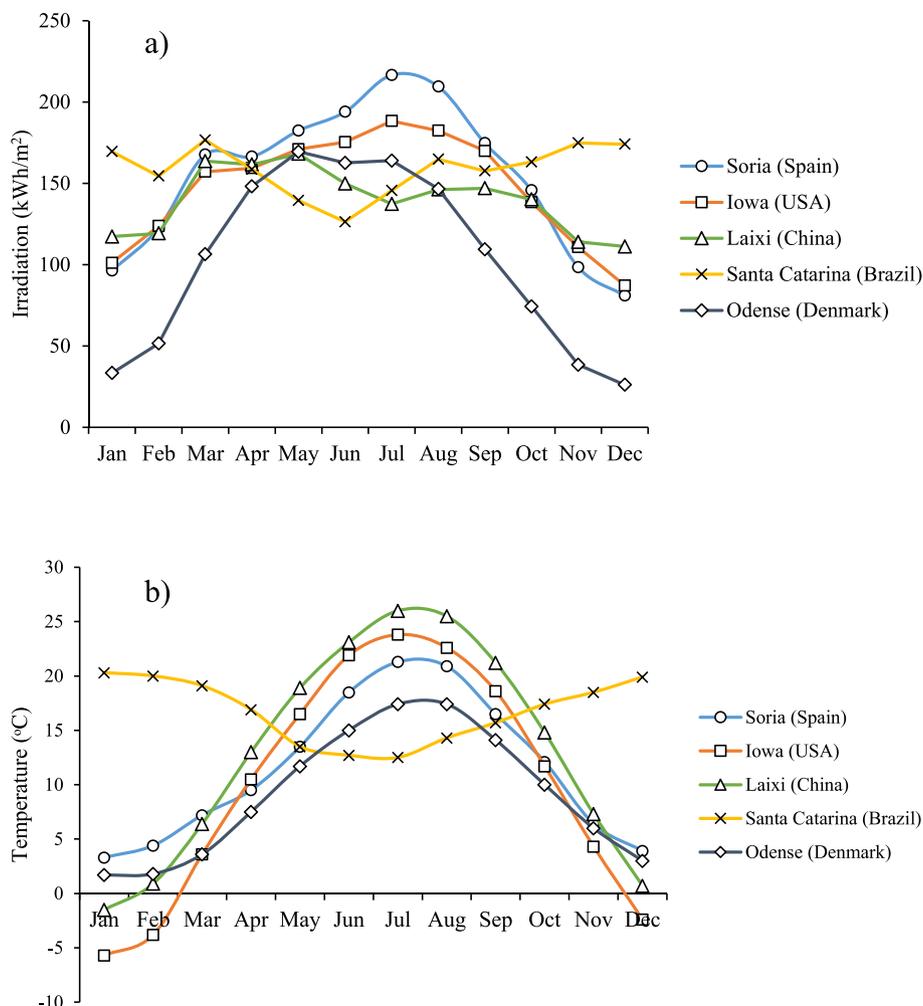
Fig. 2. (a) Average monthly temperature (b) and ambient irradiation in each location selected.
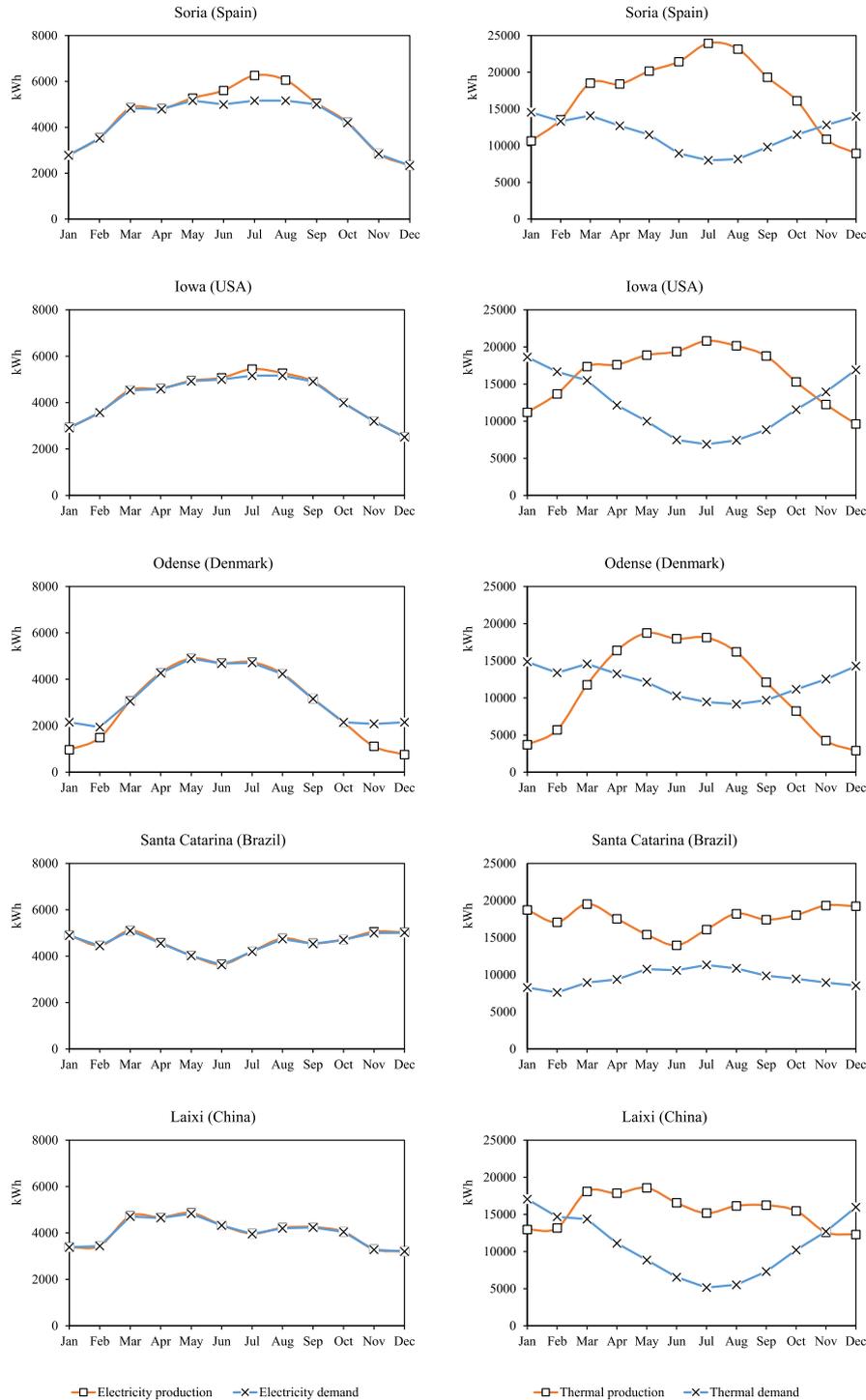
Fig. 3. Electrical (left) and thermal (right) production and demand for the study locations: a) Soria (Spain); b) Iowa (USA); c) Odense (Denmark); d) Santa Catarina (Brazil); e) Laixi (China).

defined as the 2% of the capital cost (CAPEX) per year for the whole system [41,42].

3. Results and discussion

3.1. Temperature and irradiance conditions

The different climate scenarios considered in the chosen regions are depicted in Fig. 2a and 2b, showing the mean monthly irradiance and ambient temperatures for the five locations. Laixi (China), Iowa (USA) and Santa Cataria (Brazil) have a similar temperature pattern along the year with a hot summer, feature of Köppen classification Dwa, Dfa and Cfa, respectively. The summers reach high temperatures with an average of 26 °C in Laixi or 23.8 °C in Iowa in July. Soria (Spain) and Odense (Denmark), with a warm summer, below an average temperature of 22 °C, have a Köppen clarification Csb and Cfb, respectively. Moreover, the winter temperatures are colder in Iowa and Laixi with −2.4 °C in December and −1.6 °C in January, respectively. On the other hand, the
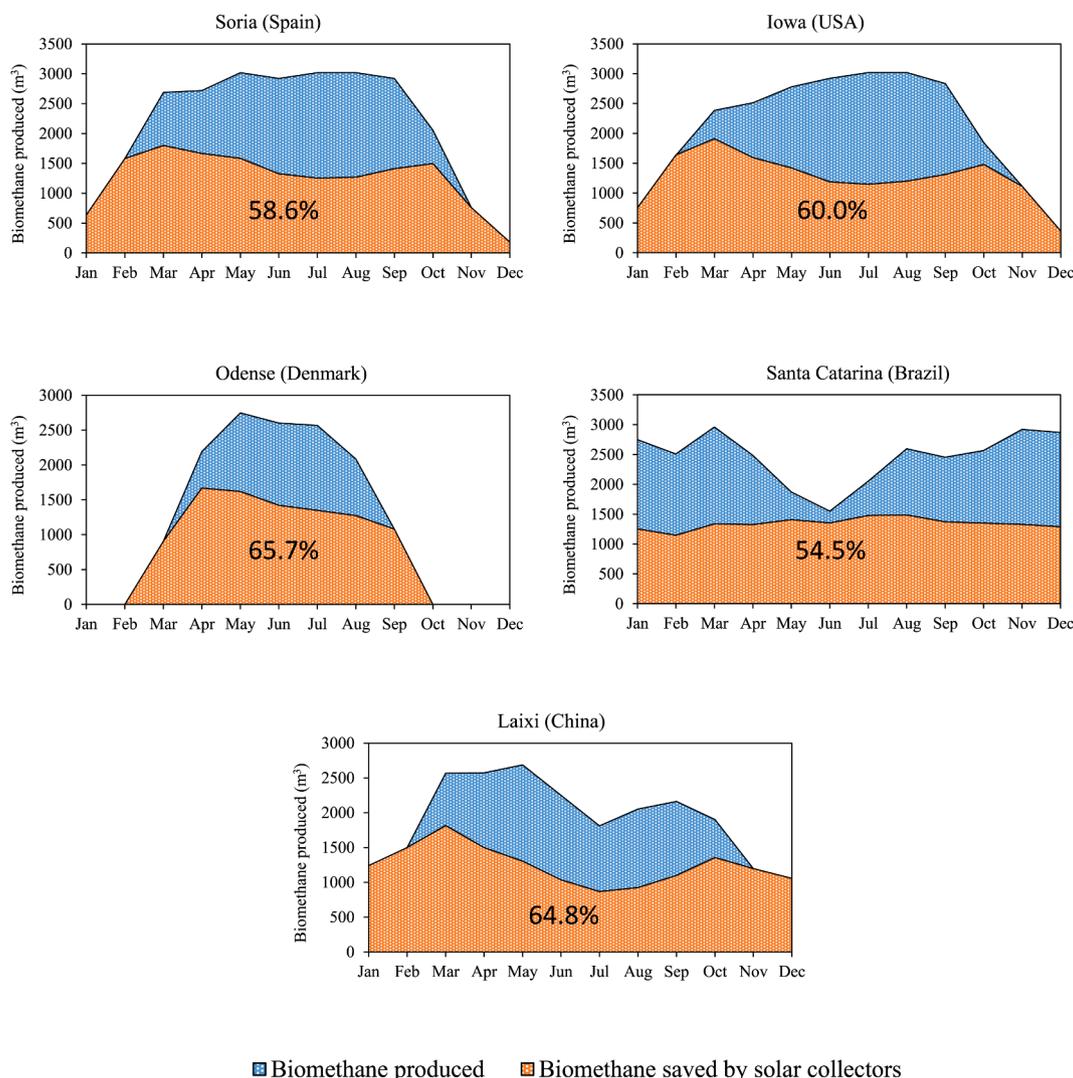
Fig. 4. Biomethane produced by the proposed hybrid system (blue colour) and biomethane saved by solar collector (red colour) in a) Soria (Spain); b) Iowa (USA); c) Odense (Denmark); d) Santa Catarina (Brazil); e) Laixi (China).

availability of sunshine has the same pattern in Soria, Odense, Iowa and Laixi, characterised by a high irradiation during summer. The lowest irradiance levels correspond to Odense, with minimum of 11.6 kWh/m^2 in December. On the other hand, Soria presented an annual average irradiation of 134.9 kWh/m^2 with a maximum of 230.7 kWh/m^2 in July. The case of Santa Catarina has a totally different performance with a more persistent irradiation throughout the year.

3.2. Energy balances

Fig. 3 displays the system's energy production and demand, calculated using monthly data for each location. Biogas conversion into biomethane was limited by electricity availability, especially in winter months when the low solar energy production compromises the operation of the upgrading system. Similarly, the thermal production was insufficient during the months of lower temperatures and solar radiation in the locations with cold (continental) climate such as Odense (Denmark) or Iowa (USA). Under these conditions, thermal requirements are covered by biogas combustion and upgrading is not operated as can be seen in Fig. 4. The subtropical conditions of Santa Catarina (Brazil) resulted in the highest biogas transformation to biomethane, accounting for 83.3% of total biogas produced in the digester. Odense presented the lowest conversion rate, with an annual average value of 39.7%. The other locations, belonging to temperate or even cold

climates, presented a higher radiation in winter months and reached average biomethane production considerable higher than Odense, between 64.7 and 71.7%.

The most adverse circumstances were discovered in Odense simulation, in which the system was unable to meet the necessary electricity demand. This could lead to a loss of control over the anaerobic digestion process occurring within the reactor, and therefore another electricity source would be needed. It is, therefore, the only case where the proposed hybrid system is not recommended in isolated installations. Under these conditions, all of the biogas produced must be used to preserve the reactor temperature.

In the rest of the locations, only a part of the production, in greater or lesser quantity, would be used to maintain the temperature of the digester, but in any case, ensuring its operability and the biomethane generation through the year. Iowa and Soria (Spain) presented a similar performance with the central months of the year with an energy generation surplus that guarantees the production of 100% biomethane, and the months of November, December and January where more than 75% of the biogas would be consumed in the boiler.

In Santa Catarina and Laixi (China), with more constant irradiation conditions during all months (a deviation of less than 50 kWh/m^2), the system can maintain the same operation throughout the year, even though Laixi experience very cold months in winter (temperatures below 0 °C in January). These findings confirmed the soundness of the
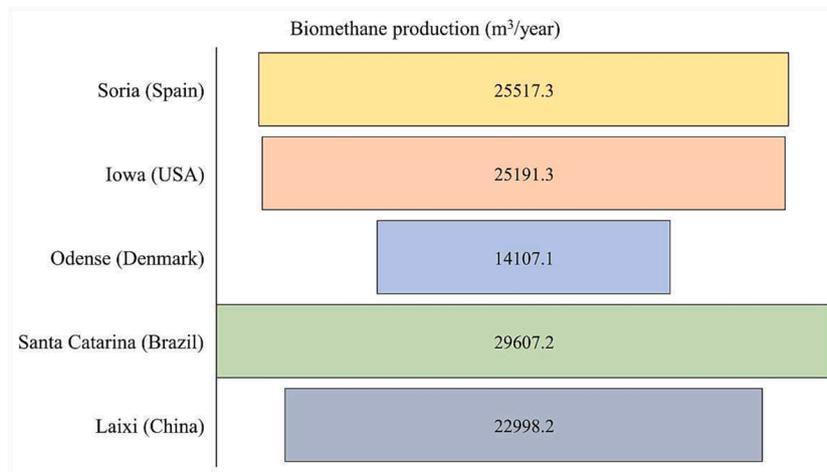
Fig. 5. Yearly biomethane production for the study locations.

Table 5
Economic analysis for the PV/T solar system implementation for each study location.

	Unit	Photovoltaic/Thermal (PV/T) hybrid solar system					
		Soria (Spain)	Iowa (USA)	Odense (Denmark)	Santa Catarina (Brazil)	Laixi (China)	Promedium
Capital Cost	USD kW^{-1}				3055		
Operating Cost	USD kW^{-1} y^{-1}				61		
Lifetime	y				20		
Discount rate	%				4.5		
Biomethane	m^3 y^{-1}	17,077	16,861	12,945	16,132	16,034	15,810
Biomethane	kWh y^{-1}	179,312	177,037	135,923	169,391	168,362	166,005
Economic price	USD kWh^{-1}	8966	8852	6796	8470	8418	8300
Equipment cost	USD y^{-1}	7485	7485	7485	7485	7485	7485
Capital costs	USD Nm^{-}3	0.438	0.444	0.578	0.464	0.467	0.473
LCOE	USD kWh^{-1}	0.042	0.042	0.055	0.044	0.044	0.045

proposed system for continental temperate climates (Dwa in Köppen classification).

In all scenarios, heat surplus is produced during the warm periods in temperate climates and through all year in tropical areas. In the particular case of electricity, the production matched the total demand of the integrated facilities, since the energy required by the upgrading system was adjusted to the availability of solar energy. Energy excess, which could seem as a disadvantage since it would force to dissipate the heat to avoid O&M problems, is herein presented as an opportunity due to the high energy demand of swine farms [43]. Other possibilities for excess heat dissipation can include regeneration of sorbents used in desulfuration and water removal from processed biomethane [44,45].

Fig. 4 illustrates the biomethane savings achieved through the operation of the digester with the support of PV/T solar collectors. The annual data ranges from 54.5% in Santa Catarina to 65.7% in Odense. In this context, the winter season is particularly critical due to the low temperatures, especially in cold climate regions like Iowa (Dfa) and Laixi (Dwa). In these regions, the surplus energy generated by the hybrid solar system drives the biomethane production.

On the other hand, the annual volumes of biomethane produced is presented in Fig. 5, where the values range between 14,107 m^3 for the case of Odense and 29,607 m^3 for Santa Catarina. This difference of more than 50% is likely due to the most unfavourable months in terms of the amount of solar energy available. In Soria, Iowa and Laixi the annual production is similar, averaging 25,000 m^3 of biomethane.

The destination of biomethane will depend on the location and needs of the farm in its daily operation. With a close accessibility to the natural gas grid, injection into the network would be an alternative, ensuring a gas composition according to the supply regulation in each location and with the only requirement to adjust the gas pressure to about 4 bars at

the network inlet [46]. When a microgrid is available on-site, a more direct use of biomethane could be made with electricity generation through an engine, heat generation with boiler or cogeneration. These energy networks are being studied and implemented in countries such as Sweden, Bangladesh or India [47,48]. Finally, if the farm itself has energy requirements, it can develop its use directly on-site. Since the chemical absorption upgrading technology guarantees a biomethane quality above 95% [49], the produced biomethane could also be used as a biofuel for CNG vehicles after gas compression [50]. This direct use of biomethane emerges as a renewable decarbonization option in rural areas, where integrated management solutions for agricultural and livestock wastes could transform the primary sector from an energy consuming into an energy producing sector.

3.3. Economic analysis

Table 5 displays the results of the economic evaluation in terms of LCOE over a 20-year operational period. The CAPEX has been calculated at 3055 USD/kWh, representing approximately a 50% increase compared to a photovoltaic system and 20% more than a thermal system [51,52]. However, despite these higher initial costs, the hybrid panel-based system was over 40% more profitable. In addition, a considerable reduction in land utilization is achieved compared to conventional photovoltaic and thermal panels.

On the other hand, the obtained LCOE values for the target regions ranged from 0.042 USD/kWh in Soria to 0.055 USD/kWh in Odense, with an average value of 0.045 USD/kWh considering the five locations. This indicates that implementing a hybrid solar system in an anaerobic digester is highly competitive when compared to the weighted average LCOE of electricity generation projects from bioenergy sources, which

stands at 0.06 USD/kWh according to the global analysis by the Renewable Energy Agency, (2022), and an average value of 0.10 USD/kWh for biogas projects [53,54].

4. Conclusions

A novel system combining anaerobic digestion and solar hybrid panels was assessed as an alternative to biogas and biomethane generation in areas without access to the electricity grid. This configuration will ensure a higher energy yield and access to bioenergy in isolated communities. The high temperatures and particularly, the availability of sunlight, will favour this hybrid system in terms of energy efficiency and conversion to biomethane as a substitute for natural gas, with maximum values in tropical areas, up to 83.3% of its potential, and minimum in cold temperate climates, less than 40 % in annual average. Temperate climates allow for intermitting production of biomethane with a marked seasonality that limits the upgrading operation to warm months. Solar hybrid panels can provide sufficient electricity for biogas/biomethane generation in any of the locations studied. On the contrary, thermal energy production limited the total self-sufficiency in the particular case of temperate regions. Finally, the economic study revealed that the PV/T hybrid solar technology proposed for enhancing the conventional anaerobic digester boasts a remarkably competitive LCOE value when compared to other energy sector technologies.

CRediT authorship contribution statement

Alfonso García Álvaro: Conceptualization, Methodology, Writing – original draft. **César Ruiz Palomar:** Methodology. **Raúl Muñoz Torre:** Supervision, Writing – review & editing. **Daphne Hermosilla Redondo:** Supervision. **Ignacio de Godos Crespo:** Supervision, Funding acquisition, Project administration, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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References

[1] Zheng X, Streimikiene D, Balezentis T, Mardani A, Cavallaro F, Liao H. A review of greenhouse gas emission profiles, dynamics, and climate change mitigation efforts across the key climate change players. J Clean Prod 2019;234:1113–33. https://doi.org/10.1016/J.JCLEPRO.2019.06.140.

[2] European Parliament, Regulation (EU) 2018/1999. Governance of the Energy Union and Climate Action. Dec. 2018.

[3] del Río P. Analysing future trends of renewable electricity in the EU in a low-carbon context. Renew Sustain Energy Rev 2011;15(5):2520–33. https://doi.org/10.1016/j.rser.2010.12.013.

[4] Yaqoot M, Diwan P, Kandpal TC. Review of barriers to the dissemination of decentralized renewable energy systems. Renew Sustain Energy Rev 2016;58:477–90. https://doi.org/10.1016/j.rser.2015.12.224.

[5] Álvaro AG, Palomar CR, de Almeida Guimarães V, Hedo EB, Torre RM, de Godos Crespo I. Developmental perspectives of the biofuel-based economy. In: Bandh SA, Malla FA, editors. Biofuels in circular economy. Singapore: Springer Nature Singapore; 2022. p. 133–56. https://doi.org/10.1007/978-981-19-5837-3_9.

[6] Palomar CR, García-Alvaro A, de Almeida Guimarães V, Hedo EB, Muñoz R, de Godos Crespo I. Biofuels in low carbon economies and societies. In: Bandh SA, Malla FA, editors. Biofuels in circular economy. Singapore: Springer Nature Singapore; 2022. p. 31–58. https://doi.org/10.1007/978-981-19-5837-3_3.

[7] Deepanraj B, Senthilkumar N, Ranjitha J, Jayaraj S, Ong HC. Biogas from food waste through anaerobic digestion: optimization with response surface methodology. Biomass Convers Bioref 2021;11(2):227–39. https://doi.org/10.1007/s13399-020-00646-9.

[8] Alvaro AG, Palomar CR, Redondo DH, Torre RM, de Godos Crespo I, Simultaneous production of biogas and volatile fatty acids through anaerobic digestion using cereal straw as substrate, *Environ Technol Innov*, 2023;103215, doi: 10.1016/J.ETI.2023.103215.

[9] Chozhavendhan S, et al. Current and prognostic overview on the strategic exploitation of anaerobic digestion and digestate: A review. Environ Res 2023;216:114526. https://doi.org/10.1016/j.envres.2022.114526.

[10] Park J-G, Park H-L, Yang H-M, Jun H-B. Simultaneously upgrading biogas and treating digestate using bioelectrochemical anaerobic trickling filter bed reactor. Sustainable Energy Technol Assess 2021;46:101218. https://doi.org/10.1016/j.seta.2021.101218.

[11] Mar KA, Unger C, Walderdorff L, Butler T. Beyond CO2 equivalence: The impacts of methane on climate, ecosystems, and health. Environ Sci Policy 2022;134:127–36. https://doi.org/10.1016/j.envsci.2022.03.027.

[12] Vaneeckhaute C, et al. Closing nutrient loops through decentralized anaerobic digestion of organic residues in agricultural regions: A multi-dimensional sustainability assessment. Resour Conserv Recycl 2018;136:110–7. https://doi.org/10.1016/j.resconrec.2018.03.027.

[13] Oosterkamp WJ, Progress in anaerobic digestion of manures. In: *Advances in feedstock conversion technologies for alternative fuels and bioproducts: new technologies, challenges and opportunities*, pp. 299–315, Jan. 2019, doi: 10.1016/B978-0-12-817937-6.00016-3.

[14] Eicke L, Eicke A, Hafner M. Solar power generation. In: Hafner M, Luciani G, editors. The Palgrave handbook of international energy economics. Cham: Springer International Publishing; 2022. p. 157–69. https://doi.org/10.1007/978-3-030-86884-0_9.

[15] Lombardi L, Mendecka B, Fabrizi S. Solar integrated anaerobic digester: Energy savings and economics. Energies (Basel) 2020;13(17):Sep. https://doi.org/10.3390/en13174292.

[16] Vassalle L, et al. The use of solar pre-treatment as a strategy to improve the anaerobic biodegradability of microalgal biomass in co-digestion with sewage. Chemosphere 2022;286:131929. https://doi.org/10.1016/j.chemosphere.2021.131929.

[17] Bamisile O, et al. Modelling and performance analysis of an innovative CPVT, wind and biogas integrated comprehensive energy system: An energy and exergy approach. Energy Convers Manag 2020;209:112611. https://doi.org/10.1016/j.enconman.2020.112611.

[18] Sarkar T, Bhattacharjee A, Samanta H, Bhattacharya K, Saha H. Optimal design and implementation of solar PV-wind-biogas-VRFB storage integrated smart hybrid microgrid for ensuring zero loss of power supply probability. Energy Convers Manag 2019;191:102–18. https://doi.org/10.1016/j.enconman.2019.04.025.

[19] Wu T, Bu S, Wei X, Wang G, Zhou B. Multitasking multi-objective operation optimization of integrated energy system considering biogas-solar-wind renewables. Energy Convers Manag 2021;229:113736. https://doi.org/10.1016/j.enconman.2020.113736.

[20] Chen Y, Guo M, Liu Y, Wang D, Zhuang Z, Quan M. Energy, exergy, and economic analysis of a centralized solar and biogas hybrid heating system for rural areas. Energy Convers Manag 2023;276:116591. https://doi.org/10.1016/j.enconman.2022.116591.

[21] Villarroel-Schneider J, Balderrama S, Sánchez C, Cardozo E, Malmquist A, Martin A. Open-source model applied for techno-economic optimization of a hybrid solar PV biogas-based polygeneration plant: The case of a dairy farmers' association in central Bolivia. Energy Convers Manag 2023;291:117223. https://doi.org/10.1016/j.enconman.2023.117223.

[22] Caetano BC, Santos NDSA, Hanriot VM, Sandoval OR, Huebner R. Energy conversion of biogas from livestock manure to electricity energy using a Stirling engine. Energy Convers Manag: X 2022;15:100224. https://doi.org/10.1016/j.ecmx.2022.100224.

[23] Alkhamis TM, El-khazali R, Kablan MM, Alhusein MA. Heating of a biogas reactor using a solar energy system with temperature control unit. Sol Energy 2000;69(3):239–47. https://doi.org/10.1016/S0038-092X(00)00068-2.

[24] Maican E, et al. Hybrid renewable energy systems for isolated farms. A review. INMATEH Agric Eng Dec. 2019;59:77–92. https://doi.org/10.35633/INMATEH-59-09.

[25] Li Q, Gao M, Li J. Carbon emissions inventory of farm size pig husbandry combining Manure-DNDC model and IPCC coefficient methodology. J Clean Prod 2021;320:128854. https://doi.org/10.1016/j.jclepro.2021.128854.

[26] Marquer P, Pig farming in the EU, a changing sector, 2010. [Online]. Available: http://epp.eurostat.ec.europa.eu/portal/page/portal/agriculture/data/ad_hoc_tables_farm_structure_survey.

[27] Ahlberg-Eliasson K, Nadeau E, Levén L, Schnürer A. Production efficiency of Swedish farm-scale biogas plants. Biomass Bioenergy 2017;97:27–37. https://doi.org/10.1016/j.biombioe.2016.12.002.

[28] Marchetti R, Vasmara C, Orsi A. Inoculum production from pig slurry for potential use in agricultural biogas plants. Sustainable Energy Technol Assess 2022;52:102310. https://doi.org/10.1016/j.seta.2022.102310.

[29] Kougias PG, Angelidaki I. Biogas and its opportunities—A review. Front Environ Sci Eng 2018;12(3):14. https://doi.org/10.1007/s11783-018-1037-8.

[30] Musgrove G, Sullivan S, Shiferaw D, Fourspring P, Chordia L, 8 - Heat exchangers. In: *Fundamentals and applications of supercritical carbon dioxide (sCO₂) based power cycles*, Brun K, Friedman P, Dennis R, Eds., Woodhead Publishing, 2017, pp. 217–244. doi: https://doi.org/10.1016/B978-0-08-100804-1.00008-6.

[31] Ward AJ, Feng L, Møller HB. Chapter 2 - Chemical absorption—amine absorption/ stripping technology for biogas upgrading. Academic Press; 2021. p. 29–55. https://doi.org/10.1016/B978-0-12-822808-1.00003-9.

[32] Tynell Å, Börjesson G, Persson M. Microbial growth on pall rings: a problem when upgrading biogas with the water-wash absorption technique. Appl Biochem Biotechnol 2007;141:299–319.

[33] Andersen IL, Ocepek M, Thingnes SL, Newberry RC. Welfare and performance of finishing pigs on commercial farms: Associations with group size, floor space per pig and feed type. Appl Anim Behav Sci 2023;265:105979. https://doi.org/10.1016/j.applanim.2023.105979.

[34] Balaji C, Srinivasan B, Gedupudi S. Chapter 7 - Heat exchangers. Academic Press; 2021. p. 199–231. https://doi.org/10.1016/B978-0-12-818503-2.00007-1.

[35] Saeidi R, Karimi A, Noorollahi Y. The novel designs for increasing heat transfer in ground heat exchangers to improve geothermal heat pump efficiency. Geothermics 2024;116:102844. https://doi.org/10.1016/j.geothermics.2023.102844.

[36] Food and Agriculture Organization os the United Nations, Meat market review 2020, 2021.

[37] Kottek M, Grieser J, Beck C, Rudolf B, Rubel F. World Map of the Köppen-Geiger climate classification updated. Meteorol Z 2006;15:259–63. https://doi.org/10.1127/0941-2948/2006/0130.

[38] Loth E, Qin C, Simpson JG, Dykes K. Why we must move beyond LCOE for renewable energy design. Adv Appl Energy 2022;8:100112. https://doi.org/10.1016/j.adapen.2022.100112.

[39] I. Renewable Energy Agency, *Renewable power generation costs in 2021*. 2022. [Online]. Available: www.irena.org.

[40] Weinand JM, et al. Global LCOEs of decentralized off-grid renewable energy systems. Renew Sustain Energy Rev 2023;183:113478. https://doi.org/10.1016/j.rser.2023.113478.

[41] Bertheau P. Supplying not electrified islands with 100% renewable energy based micro grids: A geospatial and techno-economic analysis for the Philippines. Energy 2020;202:117670. https://doi.org/10.1016/j.energy.2020.117670.

[42] Saini P, et al. Techno-economic assessment of a novel hybrid system of solar thermal and photovoltaic driven sand storage for sustainable industrial steam production. Energy Convers Manag 2023;292:117414. https://doi.org/10.1016/j.enconman.2023.117414.

[43] Jahangir MH, Montazeri M, Mousavi SA, Kargarzadeh A. Reducing carbon emissions of industrial large livestock farms using hybrid renewable energy systems. Renew Energy 2022;189:52–65. https://doi.org/10.1016/j.renene.2022.02.022.

[44] Gaj K. Adsorptive biogas purification from siloxanes—A CRITICAL REVIEw. Energies (Basel) 2020;13(10):pp. https://doi.org/10.3390/en13102605.

[45] Tran VTL, Gélin P, Ferronato C, Chovelon J, Fine L, Postole G. Adsorption of linear and cyclic siloxanes on activated carbons for biogas purification: Sorbents regenerability. Chem Eng J 2019;378:122152. https://doi.org/10.1016/j.cej.2019.122152.

[46] Keogh N, Corr D, O'Shea R, Monaghan RFD. The gas grid as a vector for regional decarbonisation - a techno economic case study for biomethane injection and natural gas heavy goods vehicles. Appl Energy 2022;323:119590. https://doi.org/10.1016/j.apenergy.2022.119590.

[47] Rahman MM, Hasan MM, Paatero JV, Lahdelma R. Hybrid application of biogas and solar resources to fulfill household energy needs: A potentially viable option in rural areas of developing countries. Renew Energy 2014;68:35–45. https://doi.org/10.1016/j.renene.2014.01.030.

[48] Sen R, Bhattacharyya SC. Off-grid electricity generation with renewable energy technologies in India: An application of HOMER. Renew Energy 2014;62:388–98. https://doi.org/10.1016/j.renene.2013.07.028.

[49] Abdeen FRH, Mel M, Jami MS, Ihsan SI, Ismail AF. A review of chemical absorption of carbon dioxide for biogas upgrading. Chin J Chem Eng 2016;24(6):693–702. https://doi.org/10.1016/j.cjche.2016.05.006.

[50] Patterson T, Esteves S, Dinsdale R, Guwy A, Maddy J. Life cycle assessment of biohydrogen and biomethane production and utilisation as a vehicle fuel. Bioresour Technol 2013;131:235–45. https://doi.org/10.1016/j.biortech.2012.12.109.

[51] Liu T, Yang J, Yang Z, Duan Y. Techno-economic feasibility of solar power plants considering PV/CSP with electrical/thermal energy storage system. Energy Convers Manag 2022;255:115308. https://doi.org/10.1016/j.enconman.2022.115308.

[52] Meriläinen A, Montonen J-H, Kosonen A, Lindh T, Ahola J. Cost-optimal dimensioning and operation of a solar PV–BESS–heat pump-based on-grid energy system for a Nordic climate townhouse. Energy Build 2023;295:113328. https://doi.org/10.1016/j.enbuild.2023.113328.

[53] Trinomics BV, Cost of Energy (LCOE). Energy costs, taxes and the impact of government interventions on investments, 2020.

[54] Fraunhofer Institute for Solar Energy Systems ISE, Levelized cost of electricity renewable energy technologies, 2021.