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Energy and economic analysis of biogas heated livestock buildings

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Abstract

The possibility to cover the annual space-heating requirements of a typical swine nursery by the methane produced using a solar-assisted anaerobic digester of innovative design, is studied for two Greek areas. Simulation is used to predict the hourly temperature and relative humidity inside the early-weaned piglet unit, along with the heating energy requirements to keep indoor conditions within pigs' production space. The methane produced by the solar-assisted anaerobic digester is also calculated using a detailed simulation algorithm. The results showed that the methane produced from the solar-assisted anaerobic digester completely ensures not only full coverage of the annual space-heating requirements of the described piglet unit for both Greek areas, but also large methane surplus which could be used in various other ways. A simple sensitivity analysis concerning the economics of the solar-assisted anaerobic digester indicated that its profitability strongly depends on to what extent the produced methane is used.

Keywords: Biogas production; Solar-heated digester; Livestock housing; Economic analysis

1. Introduction

It is well established [1] that livestock buildings housing young animals need addition of heat during cold weather periods. Such a livestock building, housing early-weaned piglets, is a swine nursery. Piglets are homeothermic animals and continuously try to keep their body temperature at 39°C through the thermal exchanges with the surrounding air [2]. Numerous studies [3–6] have shown that for early-weaned piglets, 3–4 weeks old when weaned, housed under real farm conditions, growth parameters are optimized when temperatures vary between 21°C and 29°C.

Rinaldo and LeDividich [7] in their study regarding the assessment of optimal temperature for performance of growing pigs noted that early-weaned piglets are leaner, thus less insulated and poorly protected from low air temperatures. This last necessitates additional heating during cold weather periods. Heating systems depending on electricity, propane or oil most often are used. Unfortunately, use of such energy sources leads to excessive heating costs, thus making them uneconomical. A possibly viable alternative solution is the use of part or all of the methane contained in the biogas produced by means of a solar-assisted anaerobic digester within the swine unit.

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Anaerobic digestion is a multistage microbial process, which produces a gaseous fuel, containing 50–80% methane, 20–50% carbon dioxide and some trace gases, a liquid effluent and a solid sludge. It can be used for odor control via waste stabilisation, but also for the generation of heat and/or electric power, thus offsetting part of the treatment cost [8]. In addition, methane production by anaerobic digestion of swine manure does not preclude manure's value as a fertilizer supplement, because usable nitrogen, protein and other substances remain in the treated sludge [9]. Anaerobic digestion using manure for methane production is therefore one of the most promising uses of biomass wastes because it appears to simultaneously resolve energetic, ecological and agrochemical issues [10].

The objective of this paper is to study the possibility of heating a typical swine nursery, located in two Greek areas, namely Ioannina in North Greece (lat 39°42′N, long 20°48′E) and Ierapetra in South Greece (lat 35°00′N, long 25°44′E), characterized by different climatic conditions, using the methane contained in the biogas produced by means of a solar-assisted anaerobic digester.

2. Methodology

A modified version of AGRISIM [11] is used to predict the air temperature and relative humidity inside the piglet unit, along with the heating energy requirements to keep indoor thermal conditions within pigs' production space (PS). Following Albright's [12] recommendations, PS was defined as the area enclosed by the desired minimum and maximum dry bulb temperature and corresponding minimum and maximum relative humidity. The dry-bulb temperature values were selected to coincide with piglets' optimum growth zone (i.e. 21–29°C), whereas the relative humidity values were selected based on recommendations given by CIGR [13]. The values used as limits are given in Table 1. In addition, the daily methane produced by the solar-assisted anaerobic digester is calculated using an experimentally verified simulation algorithm [14]. Hourly climatic data from both areas, including ambient air temperature and relative humidity, total solar irradiance on the horizontal surface and wind speed, are used. Monthly distribution of ambient air temperature and total solar irradiance on horizontal surface, for both Ioannina and Ierapetra, is given in Figs. 1 and 2, respectively. Finally, a simple sensitivity analysis concerning the economics of the solar-assisted anaerobic digester is undertaken.

Table 1
Piglets' production space limits

	Min. relative humidity[a] (%)	Max. relative humidity[a] (%)
Min. temperature (°C) 21	49	69
Max. temperature (°C) 29	42	62

[a]CIGR (1984).

2.1. Swine nursery description

The totally enclosed early-weaned piglet unit is mechanically ventilated. A continuous winter duct pit ventilation centrifugal fan is integrated with a wall variable speed axial fan to cover the summer ventilation rates. The unit is 7.4 m long, 5.4 m wide and 3.1–4.4 m high at the walls. The thermal resistance of the walls and the roof is $R_w = 0.6$ m^2 °C W^{-1} and $R_r = 0.3$ m^2 °C W^{-1}, respectively.

There are two seven-pen rows with a 1.4 m wide feeding alley between them. Piglets' average weight varies between 7 kg (initial) and 25 kg (final). One hundred-forty piglets are group-housed (10 piglets pen^{-1}) in pens, which are 2.0 m long, 1.0 m wide and 0.6 m high. Pen floors are made of wire mesh and pen dividers are pipe panels. Piglets are provided food and water ad libitum.

2.2. Solar-assisted digester description

The anaerobic digester is a reinforced concrete below ground level basin with 40 m^3 useful volume. Its feeding is achieved by gravity flow. Its fix cover is made of flat-plate solar collectors, which are an integral part of the roof structure. The solar collectors are coupled to a heat exchanger immersed at the bottom of the manure digester as shown in Fig. 3. The solar system is activated automatically to add heat to the manure of the digester through the heat exchanger whenever the temperature difference between the

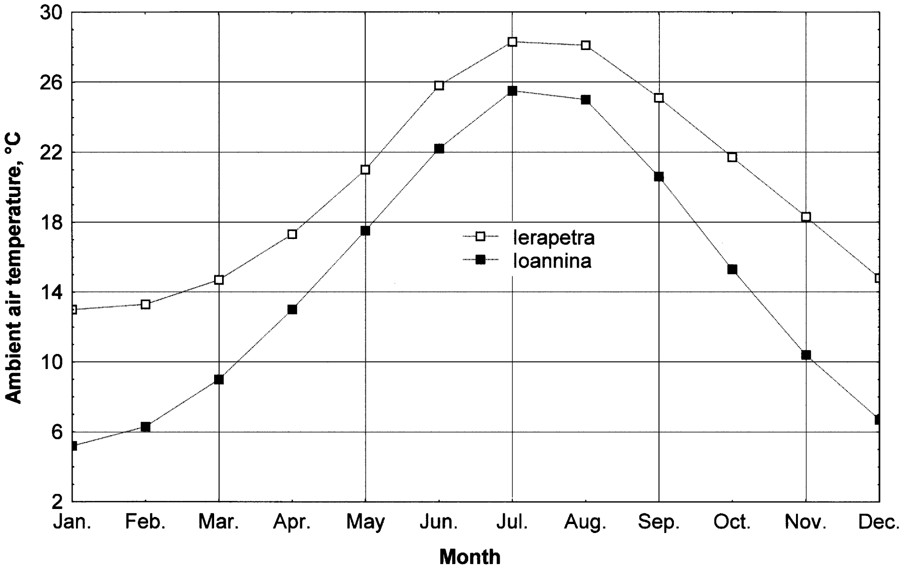

Fig. 1. Annual distribution of ambient air temperature.

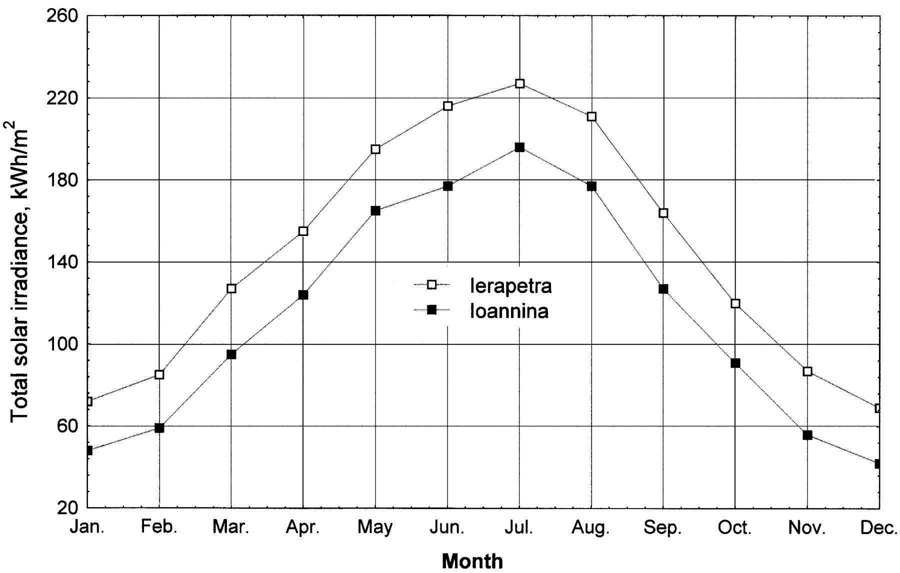

Fig. 2. Annual distribution of total solar irradiance.

collector output and the digester manure exceeds 7°C and the manure temperature is less than 35°C. The upper part of the digester, under the tilted cover, forms an airtight enclosure that is used to collect and store the daily produced biogas. It is worth noticing that the biogas stored under the titled cover in the upper part of the digester, is 76 m^3 and by itself can cover the heating load of three consecutive days at least, therefore there is no need for its continuous flow, thus no thermal losses out of the system occur. Desulphurisation

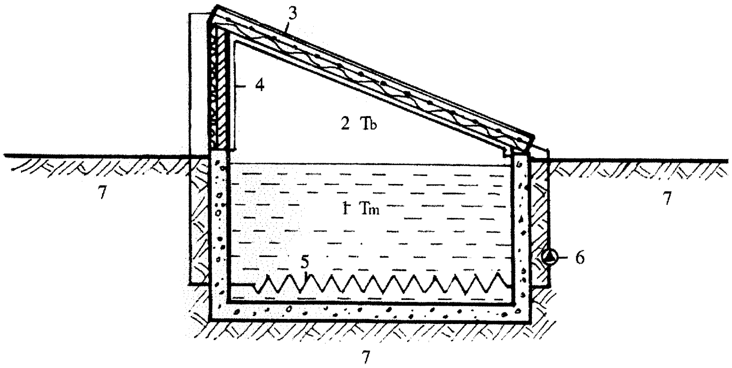

Fig. 3. Schematic diagram of the solar-assisted anaerobic digester. 1. Manure, 2. Enclosed biogas, 3. Solar collectors, 4. Plastic cover, 5. Heat exchanger, 6. Pump, 7. Ground.

of biogas is achieved by a self-constructed, cheap and simple in maintenance dry oxidation filter in the presence of iron oxide filings. The net dimensions of the digester are as follows: length: 6 m, width: 3.5 m and depth: 3 m. The walls are 0.2 m thick un-insulated. The plastic cover is well protected under a solid cover, which holds the solar collectors system. The exterior surface of the solid cover walls, are insulated with polystyrene sheets (Fig. 3). White painted plaster is used to protect these insulation sheets. Specific details can be found in [14].

The anaerobic digester was sized for 20-day retention time and was daily fed with 2 m^3 manure, while all the rest overflowed to the effluent basin. The influent Volatile Solids (vs) concentration (S_o; kgVS m^{-3}) value used was 50 according to Chen's [15] recommendations.

2.3. Simulation

Piglet unit. The dry bulb temperature and relative humidity inside the nursery building are calculated using the following time-dependent equations:

$$\sum (M_a C_a)\frac{dT_a}{dt} = \dot{Q}_s + \dot{Q}_b + \dot{Q}_f + \dot{Q}_v, \quad (1)$$

$$\rho_a V_a \frac{dW_a}{dt} = \dot{m}_a(W_o - W_a) + \dot{W}_s, \quad (2)$$

where $\sum (M_a C_a)$ is the lumped effective building capacitance (kJ k^{-1}), T_a is the inside air temperature (°C), t is the time (s), $\dot{Q}_s$ is the piglet sensible heat production (W), $\dot{Q}_b$ is the heat flow through the walls, the door and the roof (W), $\dot{Q}_f$ is the heat flow through the pen floor (W), $\dot{Q}_v$ is the heat losses due to ventilation (W), ρ_a is the density of inside air (kg m^{-3}), V_a is the volume of the inside air space (m^3), W_a is the inside air humidity ratio (kg w.v. kg^{-1} d.a), $\dot{m}_a$ is the ventilation air mass flow rate (kg s^{-1}), W_o is the outside air humidity ratio (kg w.v. kg^{-1} d.a) and $\dot{W}_s$ is the piglet latent heat (water vapor) production (kg h^{-1}).

Pig sensible and latent heat production are calculated based on recommendations given by Pedersen and Sallvik [16] for an average piglet weight of 10 kg.

The concept of sol-air temperature [12] is used in the calculation of the heat losses through the walls, the door and the roof, whereas the concept of effective heat transfer coefficient, as presented in Axaopoulos et al. [17], is used to calculate the heat losses from the pen floor.

A variable ventilation rate is adopted. At any time-step the value of the ventilation rate selected is the higher [12] among the three calculated, namely for temperature, relative humidity and CO_2 control.

Anaerobic digester. The two basic time-dependent energy balance equations concerning the manure in the digester and the biogas in the enclosure are given below. Assuming that the manure in the digester is always well mixed and consequently at a uniform temperature T_m (°C) which varies only with time, the energy balance for the manure in the digester can be written as

$$\rho_m V_m C_{pm} \frac{dT_m}{dt} = \dot{Q}_{col} - \dot{Q}_d - \dot{Q}_m - \dot{Q}_w, \quad (3)$$

where ρ_m is the density of the manure (kg m^{-3}), V_m is the volume of the manure in the digester (m^3), C_{pm} is the specific heat of the manure (kJ kg^{-1} °C^{-1}), $\dot{Q}_{col}$ is the rate of energy delivered from the solar collectors to the digester (W), $\dot{Q}_d$ is the total heat losses from the manure surface (W), $\dot{Q}_m$ is the rate of energy delivered to the incoming manure (W) and $\dot{Q}_w$ is the total heat losses through digester envelope to the ground (W).

Assuming also that the biogas temperature in the enclosure is uniform and the biogas does not flow continuously out of the system, its heat balance equation can be written as

$$\rho_b V_b C_{pb} \frac{dT_b}{dt} = \dot{Q}_{bc} + \dot{Q}_d - \dot{Q}_s, \quad (4)$$

where ρ_b is the density of biogas (kg m^{-3}), V_b is the volume of biogas (m^3), C_{pb} is the specific heat of the biogas (kJ kg^{-1} °C^{-1}), T_b is the biogas temperature (°C), $\dot{Q}_{bc}$ is the heat loss through the back of solar collectors field (W) and $\dot{Q}_s$ is the heat flow through the side walls of the cover (W). Details for the above-mentioned flows were presented in Axaopoulos et al. [14].

The methane production rate γ_v (l CH_4 l^{-1} dig. vol. day) can be calculated by the following equation, given by Chen and Hashimoto [18]:

$$\gamma_v = \frac{B_o S_o}{\text{HRT}}\left(1 - \frac{K}{\text{HRT}\mu_m - 1 + K}\right), \quad (5)$$

where B_o is the ultimate CH_4 yield (l CH_4 g^{-1} VS added), HRT is the hydraulic retention time (days), K is the kinetic parameter and μ_m is the maximum specific growth rate (day^{-1}). In our case B_o was considered to be 0.481 CH_4 g^{-1} VS.

The K parameter value can be determined by the experimentally established equation given in Hashimoto [19]:

$$K = 0.6 + 0.0206e^{(0.051*S_o)}, \quad (6)$$

where S_o is the influent Volatile Solids concentration.

Values for μ_m can be calculated [20] using the following equation:

$$\mu_m = 0.013T_m - 0.129. \quad (7)$$

Sensitivity analysis. A simple economic analysis appraisal is undertaken for methane gas produced, based on Life Cycle Cost method. This method is widely applied for determining energy systems economics. With this method all costs and benefits are discounted to their present values. The appraisal requires the synthesis of both digester performance results and a number of economic parameters. The performance data required have been calculated using the anaerobic digester simulation model. The set of presumed economic parameters (Table 2) includes digester capital cost, digester maintenance and operating cost, expected lifespan, conventional fuel cost and value of money (i.e. discount, interest, inflation). For this study the fuel oil has been presumed as the displaced conventional fuel.

Table 2
Economic parameters used

Initial investment cost	9000$
Maintenance and operating costs (% of investment)	2%
First year cost of fuel oil	4 cents kWh^{-1}
Fuel cost inflation rate	5%
Interest rate	12%
Period of economic analysis	10 years

Since most of the economic parameters change with time and geographic area and is difficult to make reliable predictions about future trends on the value of money, a sensitivity analysis based on profitability index is undertaken to evaluate the economics of methane produced under various investment costs and annual utilization factors.

3. Results and discussion

Fig. 4 shows the daily heating energy requirements of the nursery unit together with the useful methane heat produced for Ioannina and Ierapetra areas. For the calculation of the useful methane heat produced, its heating value and the boiler performance coefficient value have been taken into account. For the Ioannina area, Fig. 4 clearly shows that the decrease of heating energy requirements corresponds to an increase of methane produced and inversely. This is primarily due to the fact that an increase of the ambient air temperature and the total solar irradiance reduces the heat losses from the nursery building and increases the energy gain from the solar collectors. The flat part of the methane heat produced curves during the summer

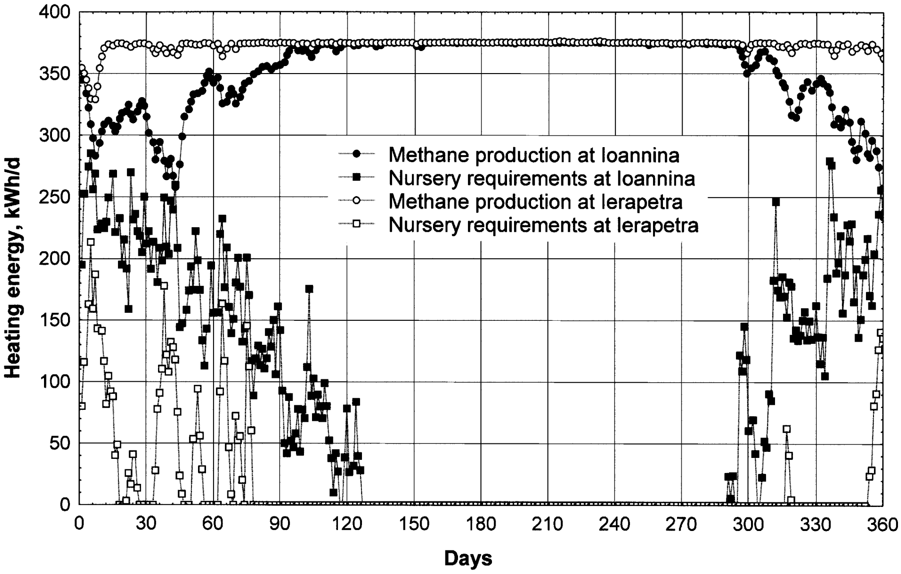

Fig. 4. Daily nursery requirements and methane production.

period, is due to the fact that the energy gain from the solar collectors is high enough to keep the manure in the digester at the upper temperature limit of 35°C. Fig. 4 also shows that at Ierapetra the non-heating period is 240 consecutive days, 50% more than those at Ioannina (i.e. 160 days). Also, at Ierapetra the methane heat produced is almost constant throughout the year, while at Ioannina the period of constant production is less. These results are due to exceptional (i.e. high ambient temperature and total solar irradiance) climatic conditions at Ierapetra.

The figure also justifies the possibility to cover the daily heating load by the methane produced every day. On the 360th day at Ioannina the daily methane production can only partially cover the heating energy requirements. The rest, are covered by the methane stored during the previous days.

The cumulative values of the heat methane produced and the heating energy requirements for the two areas are shown in Fig. 5. From these figures it can be seen that the total heat methane produced at Ioannina, is slightly lower (6%) than those at Ierapetra, whereas the total heating energy requirement is almost six times higher.

From the daily fluctuation (Fig. 4) and the cumulative (Fig. 5) curves concerning the methane heat produced, it is obvious that there is excess of methane heat produced throughout the year and especially in summer time. This surplus must be exploited to the greatest extent possible. An increase of the methane utilization factor could be achieved by heating other nursery buildings within the swine unit or by using it for cooking, lighting and water heating in farmhouse and air heating in grain dryers. An alternative solution to maximize the utilization factor is to burn the methane in an internal combustion engine for electricity production. However, in such a scheme there is a significant energy loss due to the low energy conversion efficiency. Long-term storage of the methane produced may be appropriate in some cases, but the associated pressurization equipment would be expensive and extensive safety precautions would be necessary.

For the anaerobic digester examined, a sensitivity analysis using the profitability index, versus investment cost and conventional fuel cost, for different utilization factors has been made. The profitability index is the ratio of net present value per initial investment cost. By definition, a zero value for the profitability index gives the break-even point.

Fig. 6 shows the values of the profitability index at different conventional fuel costs for two sets of lines. Each set of lines refers to different utilization factors

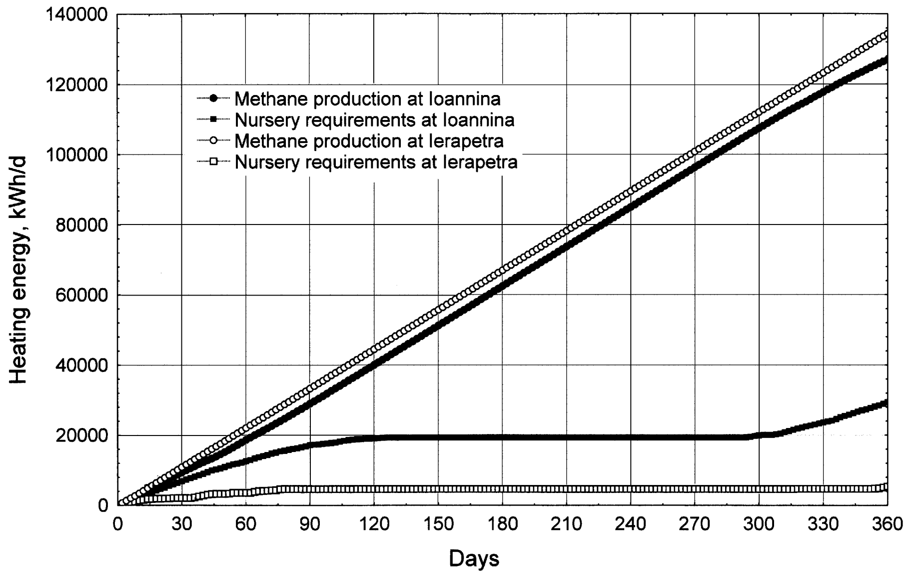

Fig. 5. Cumulative nursery requirements and methane production.

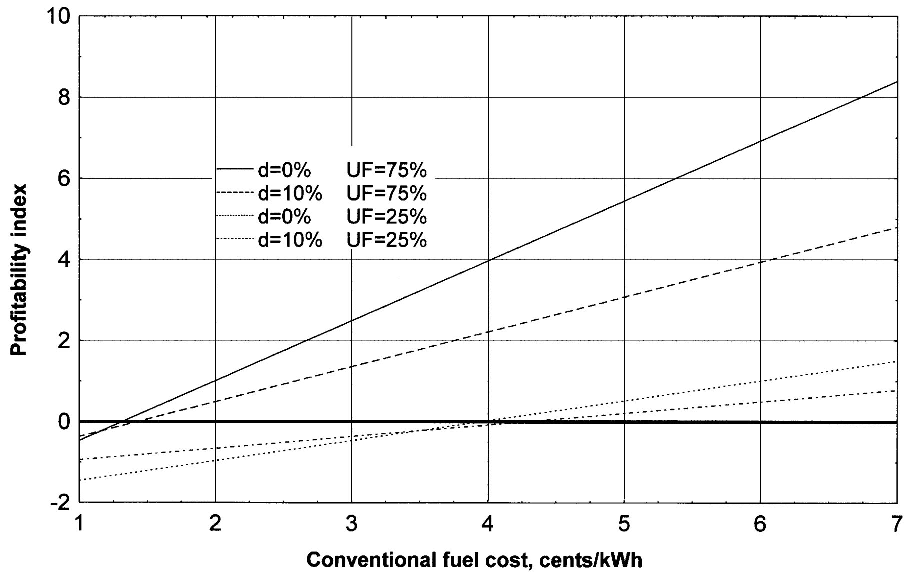

Fig. 6. Profitability index vs. conventional fuel cost (UF: utilization factor, d: discount rate).

and includes two lines, namely discount rates of 0% and 10%. The line at discount rate 0% is not very practical, but provides a good reference level. Conventional fuel costs to the right of the point of intersection of the four lines with the horizontal line, indicate net system benefits, when evaluated at the corresponding discount rate. In addition, this figure indicates that if a methane utilization factor of 25% and a discount rate of 10% are assumed, the digester is not considered economically viable until the conventional fuel cost

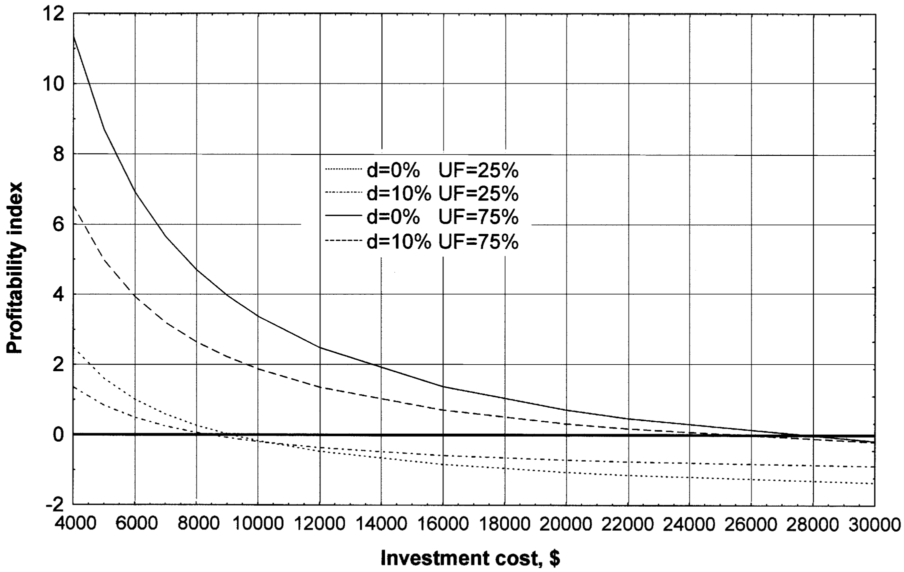

Fig. 7. Profitability index vs. investment cost (UF: utilization factor, d: discount rate).

reaches the break-even point of 4.3 cents kWh^{-1}. The conventional fuel cost would be lower if a methane utilization factor of 75% is assumed. In this case the break-even conventional fuel cost is 1.4 cents kWh^{-1}.

The current average conventional fuel cost in Greece is 4.0 cents kWh^{-1}. Consequently the proposed anaerobic digester with the given performance and presumed economic data is economically viable if the annual utilization factor is greater than 25%. Obviously, the digester is more profitable if the cost of displaced conventional fuel is more expensive than that of fuel oil. If for example electricity, with a current cost of 7.0 cents kWh^{-1}, is assumed as the displaced conventional fuel in the nursery building, the anaerobic digester would be economically viable even for a utilization factor lower than 25%.

Fig. 7 presents the profitability index versus investment cost, for two different utilization factors. Assuming an annual utilization factor of 25%, and a discount rate of 10%, the break-even investment cost is 8419$. Therefore for investment costs lower than 8419$, the system is economically viable. An investment cost to the right of the intersection point of the four curves with the horizontal line, indicates an uneconomical system and probably a governmental financial support is required so to consider it viable. It is evident that for a given investment cost, the higher the utilization factor, the higher the profitability index. Finally, the investment cost versus the produced methane cost for different utilization factors is given in Fig. 8.

Assuming an investment cost of 9000$ (civil works: 4115$, solar system: 2940$, compressor system: 735$, heat exchanger: 435$, automation: 185$, plastic films: 350$ and others: 240$) and a discount rate of 10%, the methane cost varies from a low of 1.4 cents kWh^{-1} to a high of 5.8 cents kWh^{-1} depending on the utilization factor. Therefore, high investment cost can be justified if the utilization factor is high.

The annual parasitic energy consumed (calculated as the sum of monthly measurement) was 42 kWh for the solar system and 404 kWh for the compressor system. For agricultural purposes the price per kWh in Greece is 3.2 cents, thus the total annual operating cost is approximately 15$. The annual maintenance cost (i.e. part-time inspection) is approximately 165$. Therefore, the total annual maintenance and operating costs account for 180$ (i.e. 2% of the initial investment).

The economic appraisal did not include the process' positive effects on the pollution and the odor control, along with the possible use of the dewatered solids sludge for odorless fertilization and the liquid effluent

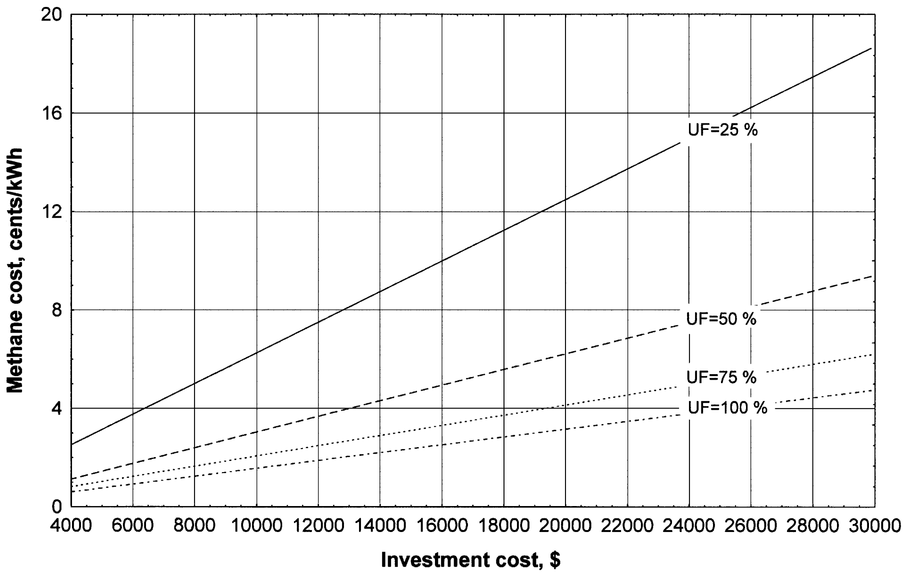

Fig. 8. Methane cost vs. investment cost.

for irrigation. However, when pollution control is the primary concern, the economics of such systems would be more favorable.

4. Conclusions

- The methane produced from the described solar-assisted anaerobic digester and for both Greek areas completely ensures not only coverage of the annual space heating energy requirements of the described early-weaned piglet unit, but also large methane surplus which could be used in various other ways.
- The profitability of the anaerobic digester strongly depends on to what extend the produced methane is used.
- Considering the existing climatic and economic conditions in Greece, the proposed system seems to be an attractive economic investment.
- Similar plants should be encouraged by the national economic and environmental policy, not only as a means of waste management, but also as alternative energy sources.

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