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Net Energy Performance of Full-Scale Mesophilic Anaerobic Digesters under Variable Climate and Mixing Conditions

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Abstract - Anaerobic digestion (AD) is a popular green technology that can transform organic waste into methane-rich biogas. However, the energy requirements for heating and mixing significantly influence the net energy balance of full-scale digesters. This study presents a consistent, computation-based energy balance to evaluate the operational conditions of a mesophilic continuous stirred tank reactor (CSTR) in terms of being energy positive or negative. A 2000 m³ digester treating 15% total solids (TS) manure and food waste at 37°C with a hydraulic retention time of 25 days was simulated under various ambient temperatures, insulation levels, mixing rates, and methane yields. We assigned a conservative yield of 0.22 $m^3\ CH_4\ kg^{-1}$ VS to estimate the amount of methane produced. Finally, we considered 3.5 kWh $m^{-3}\ CH_4$ for conversion to electricity production, assuming the technologies operate effectively on average. We applied a U–A heat exchanger (HX) and attempted to determine the heat loss and mixing energy, which ranged from 1 to 3 W m^{-3}. Over 6,000 kWh of net energy per day were available when the temperature was approximately 15°C, while less than 100 kWh/d of biogas were produced when the temperature was below 5°C. On the other hand, cold climates, poor insulation, thick adjacent feed, and low methane yield (≤0.12 $m^3\ CH_4\ kg^{-1}$ VS, where negative values were even obtained at -17%) typically resulted in a deficit in electricity production from anaerobic digestion, which could lead to an energy-negative digester. A sensitivity analysis reveals that the dominant influencing parameters include ambient temperature, reactor U-value, and mixing power. The conclusion is that improved insulation, more effective mixing, and recovery of combined heat and power (CHP) waste heat are necessary.

Keywords: Anaerobic digestion, Energy-positive digester, Mesophilic CSTR, heating demand, Mixing energy, Methane yield.

1. INTRODUCTION

1.1 Background on anaerobic digestion

Anaerobic digestion of organic wastes is an entirely microbial process proceeding in a sequence of stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This degrades complex organic material over time into simpler compounds that, in turn, eventually become methane and carbon dioxide. Due to its capacity to stabilize waste and recover renewable energy, AD has already been extensively applied for the treatment of cattle manure, food wastes, and agro-industrial residues [1, 2, 5, 18]. The technology is increasingly a significant part of environmental waste management and bioenergy in considerable agricultural and industrial applications. Normal mesophilic (> 35–37°C) is preferred in full-scale plants due to the balance between microbial activity and low heating requirement, as well as operational stability. In comparison to thermophilic plants, mesophilic ones are more flexible in terms of feeding, easier to operate, and usually do not have such high energy demand due to the lower temperature range that has to be covered, which is why they dominate in the field of industrial biogas production.

Biogas can be used for the generation of electricity with CHP, direct thermal use, and upgrading to biomethane for injection into the grid. These routes increase the economic and environmental merits of AD plants via replacing that with fossil fuel. The latter condition contrasts the habitats of laboratory biochemical methane potential (BMP) tests, where conditions are favorable and energy neutral, and real digester consequences from energy-demanding heating/mixing throughout operation (for maintaining stable biological activity and avoiding sedimentation of solids). Such operational needs come with a high level of internal energy demands that should also be taken into account when evaluating the real energy performance of full-scale AD systems.

1.2 Concept of energy-positive vs energy-negative digesters

An energy-positive digester produces more usable energy as methane than it consumes. Biogas energy-balance studies have extensively discussed this concept [4, 13, 17]. The system needs heating to maintain mesophilic temperatures, mechanical mixing to ensure uniformity, pumping for feed and recirculation, and electrical power for monitoring and control systems. When the recoverable energy from methane is more than what the digester needs to run, it adds renewable energy to the grid or facility. An energy-negative digester, on the other hand, is one where the total amount of energy needed to run the system is greater than the amount of energy that can be gotten from the methane that is produced. These systems may still treat waste, but they may not produce more energy than they consume.

The net energy balance is defined as:

$$E_{net} = E_{CH4} - (E_{heat} + E_{mix})$$

1.3 Gaps in existing energy balance assessments

Most previous studies report gross methane production without fully accounting for full-scale operational realities [8, 14, 18], including:

- In frigid climates, site-specific heat losses can significantly increase the thermal energy demand well beyond what is predicted in the lab.
- A higher mixing power is needed when the total solids are high (TS), especially in thick substrates such as food waste and very thick manure slurries.
- Sensitivity to insulation quality and reactor design is particularly important with respect to how they influence heat transfer, stability, and overall power efficiency.

To overcome this deficiency, an easy-to-use energy accounting framework followed by a completely transparent calculation for the mesophilic 2000-m³ reactor at 15% TS (as found in commercial-scale plants) is employed in this work.

2. GAPS IN EXISTING ENERGY BALANCE ASSESSMENTS

2.1 2000 m³ CSTR configuration

The reference system in this study is a CSTR, with the amount of work being 2000 m³, having used a cylindrical form considered representative of full-scale biogas installations. The estimated liquid surface of the reactor is around 1200 m², taking into account that height-to-diameter ratios are in the range of those used for commercial digesters. The reactor is thermally insulated to prevent heat losses to the environment, which prevents a stable mesophilic condition. Mechanical stirrers are used to promote homogeneous mixing, avoiding the settling of solids, and improving the contact between microorganisms and substrates. In addition, the system is provided with an external heating loop in the heat exchanger for controlled temperature regulation of the digester contents.

2.2 Feed characteristics (15% TS manure / food waste)

Key assumptions:

- Total solids (TS): 15%
- VS/TS ratio: 0.75
- Slurry density: 1000 kg/m³
- Hydraulic retention time (HRT): 25 days

Daily feed rate:

$$\text{Feed per day} = \frac{2000}{25} = 80\ m^3/day$$

Daily TS loading:

$$80 \times 1000 \times 0.15 = 12,000\ kg\ TS/day$$

Daily VS loading:

$$12,000 \times 0.75 = 9,000\ kg\ VS/day$$

2.3 Mesophilic operation (35–37°C)

The digester temperature was maintained at about 37°C for stable mesophilic microbiology. An external ambient temperature base of 15°C is considered to represent average temperate climate conditions of full-scale performance.

3. METHODOLOGY: ENERGY ACCOUNTING FRAMEWORK

3.1 Methane production estimation

Assuming a methane yield of 0.22 m³ CH_4 per kg VS—a value consistent with cattle manure and mixed feedstocks reported by [9, 15]:

$$CH_4 = 9,000 \times 0.22 = 1,980\ m^3/day$$

Using 3.5 kWh per m³ CH_4:
Note: An electrical output of 3.0–3.5 kWh per m³ CH_4 is justified based on methane's lower heating value (~10 kWh/m³) and typical biogas genset electrical efficiencies of 30–40%. This range is empirically supported by experimental cogeneration results reported by Dalpaz et al. (2020) for high-methane biogas–fuelled engine systems.

$$E_{CH_4} = 6{,}930\ \text{kWh/day}$$

3.2 Heating energy demand

Heat loss is estimated as:

$$Q = UA(T_{in} - T_{out})$$

Where:

- $U = 0.6\ W/m^2K$
- $A = 1200\ m^2$
- $T\_in = 37°C$, $T\_out = 15°C$

$$Q = 0.6 \times 1200 \times 22 = 15,840\ W$$

Daily heating energy:

$$E_{heat} = 380\ kWh/day$$

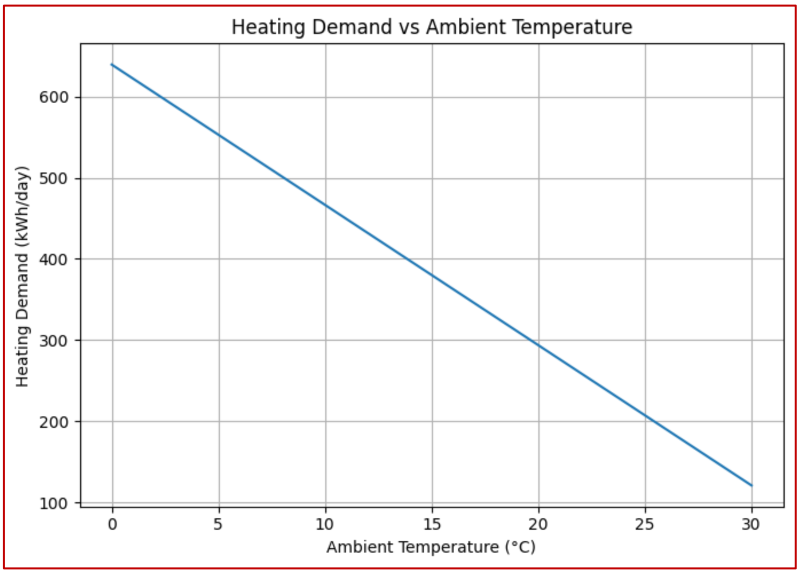

Fig -1: Heating Demand vs Ambient Temperature.

Figure 1 shows how the digester's daily heating energy needs change with the temperature outside. When the temperature outside drops, heat losses go up, which means the reactor needs more heat to stay at 37°C.

3.3 Mixing energy demand

Assuming 2 W/m³ (within the 1–3 W/m³ range commonly reported for full-scale CSTRs; [10, 11]):

$$Power = 2 \times 2000 = 4\ kW$$

Daily mixing energy:

$$E_{mix} = 96\ kWh/day$$

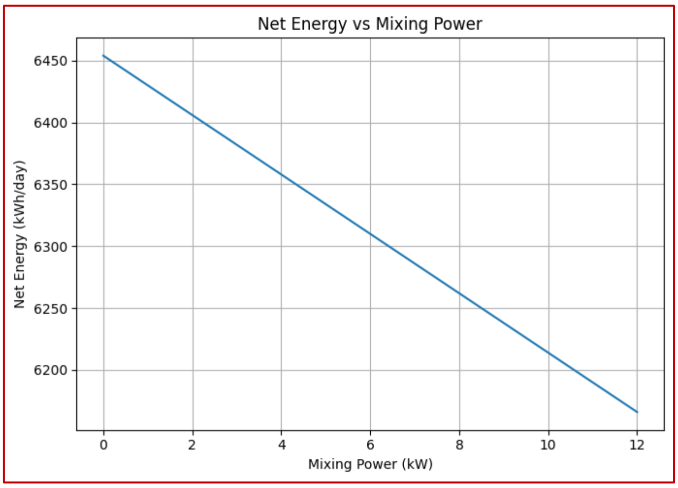

Fig -2: Net Energy vs Mixing Power.

Figure 2 shows the relationship between mixing power demand and the net energy output of the digester. As mixing power increases, the internal energy consumption rises, leading to a progressive reduction in net energy.

3.4 Net energy balance (base case)

$$E_{net} = 6{,}930 - (380 + 96) = 6{,}454 \text{ kWh/day}$$

3.5 Critical scenario (energy-negative conditions)

Worst-case assumptions:

- Ambient = 0°C
- Poor insulation
- High-viscosity feed (15% TS food waste)
- Mixing power = 12 kW

Heating demand ≈ 3,000 kWh/day Mixing demand ≈ 288 kWh/day

If methane yield drops to 0.12 m^3/kg VS:

$$E_{CH_4} = 3{,}780 \text{ kWh/day}$$

If heating rises to 6,000 kWh/day:

$$E_{net} = -2{,}220 \text{ kWh/day}$$

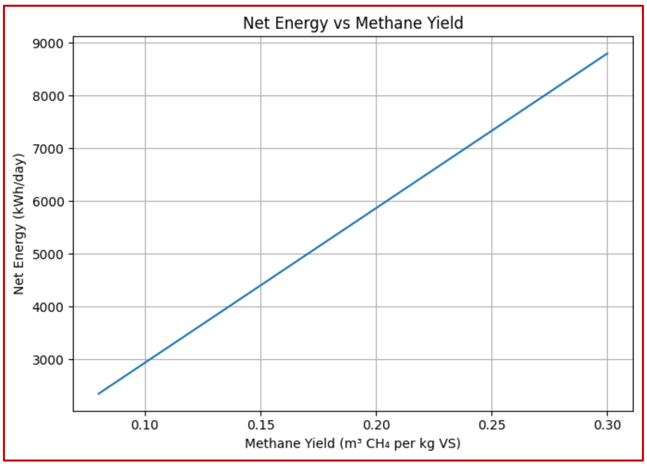

Fig -3: Net Energy vs Methane Yield.

Figure 3 shows how the digester's net energy output changes as the substrate's methane yield changes. Higher methane yields mean more energy can be recovered, while lower yields mean less energy can be recovered, which could lead to energy-negative operation.

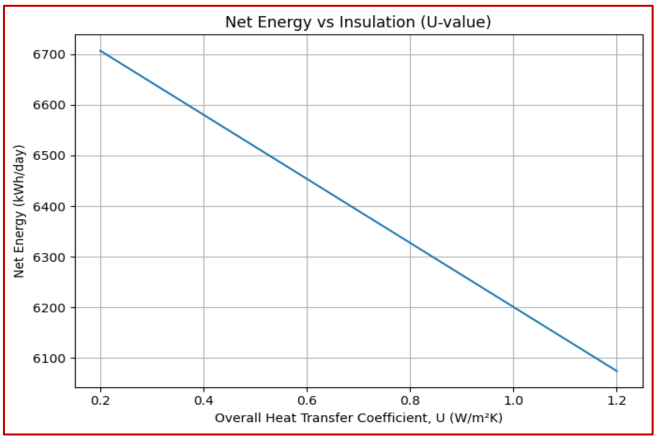

Fig -4: Net Energy vs Insulation (U-value).

Figure 4 shows how the overall heat transfer coefficient (U-value) of reactor insulation affects net energy. Higher U-values (less insulation) cause more heat to escape, which lowers the digester's net energy output.

4. RESULTS AND DISCUSSION

1. **Ambient temperature controls net energy**
   When it's cooler outside, the digester system loses more heat, so more heat must be added to keep the system running well. As heating demand goes up, a greater amount of energy from biogas will be required to maintain temperature. This means that not as much methane energy can be recovered. Consequently, the digester is not as energy-efficient because it's colder. This trend is clearly visible in Figures 1 and 2, which demonstrate that net energy decreases as the outside temperature falls.

2. **Methane yield dominates performance**
   The potential for energy recovery is related to the amount of methane produced per unit COD removed, with higher yields resulting in a more favorable overall sustainable energy balance. High levels of methane production mean that less substrate chemical energy is lost in the form of unused biogas, enabling a positive net energy performance. On the negative side, low yields mean that less energy is available as recoverable biogas energy, diminishing the economic viability of such a system. From Figure 3, it can be seen that the risk of operating in an energy-consuming state increases significantly when methane yield is lower than 0.14 m^3/kg VS.
3. **Insulation is critical**
   Thermal insulation is known to be very effective in reducing heat losses from an anaerobic digester (AD) because it restricts the external transport of internal heat. The widely spaced glass-reinforced epoxy mini-baker surfaces have very poor insulation properties, and most of the thermal energy generated escapes. The higher the U-value (which is equivalent to worse insulation), the more thermal energy is lost from the device. As shown in Fig. 4, higher U-values are related to lower net energy generated by the digester.
4. **Mixing intensity matters at 15% TS**
   A high total solids concentration results in higher slurry viscosity within a reactor, which prevents the substrate from moving and flowing freely. With increasing viscosity, more vigorous mechanical agitation becomes necessary to achieve the correct mixing and prevent separation while ensuring adequate microbial contact. This higher mixing intensity implies greater electricity consumption by the agitation systems. In Figure 5, it can be observed that the mixing energy cost may increase to slightly less than three times that of the lower-solids mode when more than 15% TS is processed.
5. **Energy components comparison**
   Methane energy is still the main recoverable energy from anaerobic digestion under most operating and climatic conditions. In a hot climate, other heating is minimal, and more of the energy content of the methane produced can be used to perform useful work. However, in a cold region, heat loss increases significantly, and much more gas must be produced to keep the digester warm. In such cases, heating may be an important—and in some scenarios, the dominant—contribution to the overall energy absorbed by the system.

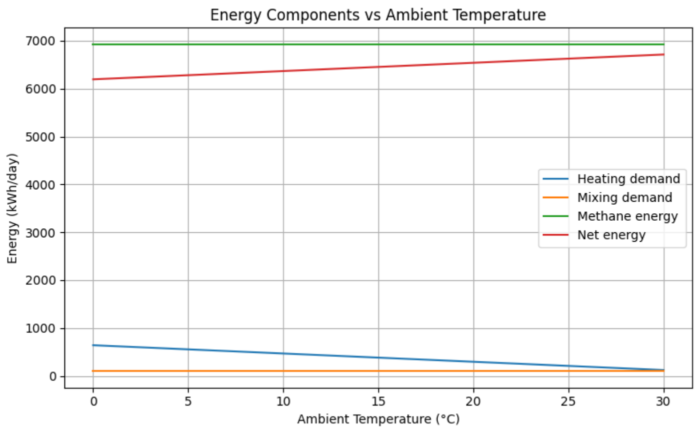

Fig -5: Energy Components vs Ambient Temperature

Figure 5 compares the relative magnitudes of methane energy, heating energy, and mixing energy across different ambient temperatures. It shows that heating demand rises sharply in colder conditions, while methane and mixing energy remain largely constant.

5. CONCLUSIONS

This report provides a mathematical model for the full-scale AD using the quantification of heating and mixing energy in addition to methane generation. Modelling a typical 2000 m^3 mesophilic CSTR operating at 15% total solids indicates that, when correctly insulated and mixed, the system generates energy under temperate conditions. Operating at 15 °C and a CH_4 yield of 0.22 m^3 CH_4 kg^{-1} VS, the digester generates approximately 6,930 kWh day^{-1} of methane power and consumes only 476 kWh day^{-1} for heating and mixing, yielding a net gain of 6,454 kWh day^{-1}.

However, net energy performance is heavily dependent on temperature and insulation. In cold areas with poor insulation, heat losses can outweigh energy gains, and the digester would be energy-negative under the worst-case circumstances. The sensitivity analysis reveals that ambient temperature, reactor U-value, and mixing intensity are the dominant factors influencing process performance.

The results illustrate that energy-positive operation through this kind of organic waste-to-renewable energy process is primarily dependent upon engineering design rather than reactor size, specifically better insulation efficiency, effective mixing, and recovery of CHP waste heat. The model provides a useful tool for assessing the energy performance of actual anaerobic digestion systems.

6. DECLARATIONS

We are the authors who conclusively affirm that this manuscript titled "Energy Positive Digesters: Quantifying When Heating and Mixing Consume More Energy Than Methane Produces" represents our own original work, which is the conclusion of a systematic review and established engineering principles. To the best of our knowledge, this study has not been presented anywhere for any academic degree or professional qualification.

7. FUNDING

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8. CONFLICT OF INTEREST

The author declares that there are no competing financial or non-financial interests that could have influenced the outcomes or interpretation of this research.

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