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Psychrophilic plug-flow digester with assisted solar heat – small-scale system feasibility

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Abstract. Paper discusses using a low-temperature biogas reactor with a solar support system technology as a management tool of biodegradable waste in small scale. A feasibility study looks at primary factors affecting anaerobic digestion process and solar heat production, design examination of a solar heating for anaerobic digester and possible technology application, also defines the multilocality of biogas, illustrates diffusion of innovation for diversification of biogas production. Analysis confirms solar heat increases efficiency and production of biogas, decreases costs and toxicity of digestate. Results show that for implementation of technology in rural areas further research in socio-economic, sourcing of feedstock and customization is needed.

Key words: plug-flow, anaerobic digester, solar heat, low-temperature, multilocal.

INTRODUCTION

Energy is a fundamental constituent in development since it stimulates and aids economic growth (Omer, 2018). The need to provide affordable energy to underprivileged communities is crucial in a global context. It is also essential for less developed European countries. Finding substitute, clean and cost-effective energy sources today has become a crucial challenge for households and national economies. One of the main factors determining this is the rising price of fossil fuels and taxes on energy sources. Economic welfare and quality of life in most countries are linked to consumption of energy, a prime factor of economic development and a traditional development indicator. Energy demand is a major source of climate change, resource use, and limiter of people's living conditions. The deployment of renewable energy on a large scale has great potential to mitigate several challenges related to ecological imbalances, significant fuel demand, health and quality of life in rural and urban areas. Energy sector stability and sufficiency are crucial for the growth of developing countries, economically less developed regions and for raising society's standard of living. The country's energy development can be met by several renewable energy sources. Renewable energy sources are energy sources that have less negative impact on the environment than conventional fossil energy. Most of the investments in the renewable energy sector are spent on materials and personnel, on building and maintaining equipment, not on expensive energy import (Balasubramaniyam et al., 2008; Rajendran et al., 2012; Shahzad, 2012). One of the promising forms of renewable energy that can help promote additional energy production is biogas production by anaerobic digestion process. Anaerobic digestion can be locally used for integration of sustainable renewable energy source solutions. Biogas is energy source that can be used as a substitute for natural gas (Mccabe & Schmidt, 2018). Also, biogas has the potential to meet the energy demand of the rural community, it can be used as a substitute for firewood or manure. Anaerobic digestion is a solid waste management tool (Bruno et al., 2009).

The production of the biogas takes place in mainly three ways, due to these needs: (1) biogas is produced in small reactors (households) in developing countries for biodegradable waste treatment and the production of gas primarily for cooking or heating applications (Gupta et al., 2012); 2) manufacturers in developed countries produce electricity and syngas from waste and energy crops (Korres et al., 2013; Miltner et al., 2017); 3) manufacturers use the anaerobic digestion process as a waste management tool and the energy produced is used to promote the company's energy self-sufficiency (Achinas et al., 2017; Nnali & Oke, 2013).

In the anaerobic digestion process, organic material is degraded by bacteria in an anoxic environment, transforming substrates (feedstock) into a blend of CH_4 and CO_2 with a few other gases such as H_2S, water vapor, and digestate - material remaining after the anaerobic digestion of feedstock. Methane formation in anaerobic digestion consists of four different processes, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Anaerobic digestion has been used for waste treatment and biogas recovery from many types of organic waste. Its numerous benefits, such as recovery of renewable energy, waste volume reduction, and reduction of odor, are well documented (Wellinger et al., 2013). Biomethane can be produced by psychrophilic (0–25 °C), mesophilic (25–45 °C) and thermophilic (45–70 °C) bacteria. In the production of industrial-scale biogas temperature is chosen from 37 °C to 70 °C, because in high-temperature conditions anaerobic digestion is faster and digestate is better disinfected (Seadi et al., 2008). This approach produces more gas in a shorter time, and retention time of the feedstock in the bioreactor is reduced. Such a method applies to a biogas plant for commercial gain. However, this approach involves some drawbacks in the context of efficient use biomass, such as inefficient processing (digestion) of raw materials, process instability (inhibition), a potential decline in biogas production and stoppage of the process. In-depth knowledge about microorganism community dynamics are needed for more understanding of and controlling the process. The formation of biomethane at low temperatures (10–20 °C) is approximately twice as slow as in the mesophilic (25–42 °C) conditions. In general, such a biomethane production process is slower, but the process is more stable. Feedstock in bioreactor require twice as much retention time and the amount of biomethane produced per day is lower. Longer hydraulic retention time provides better recycling efficiency of biomass and biomethane concentration in biogas is higher (Gruduls et al., 2017). And less likely inhibition of bacteria because of volatile fatty acids, ammonium, heavy metals. Based on the basic principles of bioeconomy, the production of biomass in psychrophilic conditions is the most suitable technology for recycling biomass waste. Biogas production can be carried out from 100 mL to 10,000 m^3 bioreactors (Venkata Mohan et al., 2016; Filho et al., 2018).

The solar collector is a special heat exchanger that converts solar irradiation energy to the thermal energy of the working fluid in solar thermal applications. To use solar heat, the solar collector absorbs solar radiation as heat that is then transferred to the working fluid (air, water or oil). Solar collectors are usually divided into two categories according to concentration factors: non-concentrating collectors and concentration collectors. The non-concentrating collector has the same intercept zone as its absorbing zone, while the solar collecting concentrating solar collector usually has concave reflective surfaces to intercept and concentrate solar radiation on a much smaller capture zone, resulting in increased heat flow so that the thermodynamic cycle can achieve a higher Carnot efficiency working at higher temperatures. The flat-plate collector is a non-concentrating solar collector, the simplest and most widely used. To prevent overheating of the system, the heat absorbed by the suction plate must be quickly transferred to the working fluid. After the solar collectors have collected the heat, it must be efficiently stored. Thus, it is very important to create an economical energy storage system (Tian & Zhao, 2013). Absorbent plate, usually a metal, is connected to a series of risers (or tubes) which are connected to the upper and lower tubes of larger diameter, called headers. Solar energy generated on the absorption plate is transferred to the fluid flowing through the pipes. Cooled water gets to the lower header and the heated water leaves the top header. Receiver is usually located in an isolated box with a transparent lid. The flat plate collectors have a temperature range of about 30–80 °C. Flat collectors can be made of different materials and different construction methods are possible. As a result, they are designed for different applications, they may have different performance and costs. For example, two layers of glazing are sometimes used to improve thermal performance (MPMSAA, 2009).

Regardless of what temperature anaerobic digestion takes place, energy is needed to keep the process at a reasonable temperature and time to produce biogas. Researchers need to find a way to provide the necessary energy for a minimal cost. If the temperature is below 15 °C in anaerobic digestion biogas production become insignificant. This problem can be overcome by using solar energy to support a biogas reactor or plant (Alkhamis et al., 2000; Chamoli et al., 2011) or by using electricity or heat from grid. Heat in biogas digester is required in three aspects: 1) the heat required to raise feedstock temperature; 2) to compensate for heat losses within the digester; 3) to compensate for losses that could occur in the pipelines between the heat source and the bioreactor. The heat required is provided by a collector that absorbs solar radiation and transforms it into the heat absorbed by the heat transfer fluid passing through the collector (Gupta, 2010a).

Unequivocally mini-scale psychrophilic biogas production is disadvantageous from an economic point of view but there are pros for such a system – the production of biogas in mini-scale low-temperature digestion allows it to use the opportunity to produce energy for self-consumption with relatively small financial investment. Also reduce the amount of bio-waste to manage, the negative environmental impact of both waste disposal and climate change, and reduce costs associated with management of waste (Balasubramaniyam et al., 2008; Rajendran et al., 2012; Anyaoku & Baroutian, 2018). The combination of renewable energy sources in a hybrid system provides more efficient energy production and facilitates market entry of such systems (Agarkar & Barve, 2011). A shift to distributed renewable energy resource are useful way to increase overall energy grid resilience.

A feasibility study is an investigation of the viability of a project idea. It was employed to assess potential and determine if proceeding with it would be advantageous. Techno-economic, environmental, and legal aspects of the project are often reviewed, along with any potential challenges that could arise. Renewable energy system discussed are considered for temperate region biowaste treatment to produce heat. Developing of bioenergy in small scale production will facilitate transition to self-sustaining full cycle biosystem. Approach would invigorate management of household, horticulture and farm biodegradable residues and will reduce problems associated with the release of these residues into the environment, while the produced biogas can be used for heating and cooking applications of households. Also, the hybrid biogas digester unit is a tool for renewable energy integration as it is diffuser of renewable energy sources and techniques. The main aim of the paper is to do a feasibility study for a psychrophilic to mesophilic anaerobic digestion reactor with solar system support for biogas and heat production.

MATERIALS AND METHODS

Assumptions for Analysis

Various assumptions about the state of the system were made to simplify the system for a feasibility study. System components and their functions were based on references from the literature. Biogas yield is assumed to be determined only by the digester temperature and feedstock used. Heat produced by solar collectors are sufficient to heat digester to get the desired temperature; heat exchangers are adiabatic meaning heat loss with the environment can be avoided.

Reactor volume

Individual parameters for reactor size and solar support system were calculated for quantification purpose of technology. The volume of the reactor was chosen to be adapted with the daily amount of feedstock and the degradation rate of the feedstock. Amount of biodegradable waste is equivalent to 130 kg of food waste per day. Two parameters were used to calculate the volume of the digester - organic loading rate (*OLR*) and the hydraulic retention time (*)*), to achieve the right balance for reactor volume (Khoiyangbam et al., 2014).

The *OLR* describes as the amount of feed processed per unit of the reactor volume per day, expressed in kilograms of total volatile solids (TVS) per day and per cubic meter of the digester (kg TVS m^3 day^{-1}) (Khoiyangbam et al., 2014). The ORL was calculated by Eq. (1). To calculate the organic loading rate, TS and *TVS* values were adapted from Mhandete et al. (Mshandete et al., 2004). The higher the *OLR*, the more sensitive the system becomes and monitoring system is required to ensure process efficiency. Plug-flow digesters function with a higher *OLR* than traditional digesters, up to 10 kg VS m^3 day^{-1} (Nathalie Bachmann, 2013). Therefore, *OLR* was increased three times.

$$OLR = \frac{SI \cdot TS \cdot TVS}{DV} \tag{1}$$

where SI – substrate input, kg day^{-1}; TS – total solids %; TVS – total volatile solids %; DV – digester volume, m^3.

The) is the theoretical time period that the substrate stays in the digester (Nathalie Bachmann, 2013). The *)* was calculated from Eq. (2):

$$HRT = \frac{NDV}{SI}, \tag{2}$$

where NDV – net digester volume, m^3; SI – substrate input, m^3.

It describes the mean retention time. *)* deviates from this value. *)* must be chosen to allow adequate degradation of substrates without increasing the digester volume.

Energy production

To evaluate the potential energy produced in from the biogas system the energy production in this study was observed. Biogas is directly used for heating as a substitute for natural gas, according to (Khoiyangbam et al., 2014) one cubic meter of biogas with 60% methane is equivalent to 4,713 kcal or 4.698 kWh electricity. The amount of energy in a year from those aggregates was calculated by Eq. (3):

$$\mathrm{T_E} = \mathrm{E_b} \cdot T_b \cdot E_V, \tag{3}$$

where $\mathrm{T_E}$ – total heat energy per year in kJ; $\mathrm{E_b}$ – calorific value of 1 m^3 of biogas with 60% CH_4; T_b – total biogas volume in m^3 annually; E_v – energetic value of 1 kcal in kJ.

Required Solar Collector Area

Solar collector yield or the useful thermal output of the collectors depends on the total irradiation onto collector area and the collector efficiency. For estimating the required solar collector area Zijdemans (Zijdemans, 2012) provides a simple calculation method:

$$A_{\mathrm{abs}} = \frac{Q_{\mathrm{demand}} \cdot SF}{Q_{\mathrm{sol}}}, \tag{4}$$

where, A_{abs} – collector absorber area; Q_{demand} – total heat demand; SF – desired solar fraction; Q_{sol} – Collector yield (Jakobsons, 2015).

RESULTS AND DISCUSSION

The Framework and Concept of Technology

In northern Europe production of biogas developed in the middle of the last century as an instrument for wastewater treatment, reducing the bulk of sludge and biogas is used for wastewater station heating. But at the end of the last century, because of the change in the political system in Eastern Europe, biogas production declined to almost zero. In Sweden this was the period when biogas shifted from by-product to the desired energy carrier - it became possible to create a profitable company and entrepreneurs and municipalities worked together to produce vehicle gas and to increase energy efficiency. Since the end of the last century, with the advent of technology and the diversification of different technological styles increased the efficiency of the process technology. Main objective of the technology being studied is to increase the amount of renewable energy at the national level to ensure regional investment potential of the energy sector by increasing the share of biomethane and solar energy in the final energy consumption of renewable energy sector of Latvia. The main importance of a technological solution is to maximize digestion of organic residues by getting higher concentrations of methane in biogas and digestate with less organic material. Psychrophilic anaerobic digestion with assisted solar heat is a way how to maximize methane content and decrease organics in digestate (Su et al., 2011). Technology is intended for non-profit and autarky, later for economic benefit of biogas plant owners. In this work, we combine biogas production in the mini to small-scale as the main renewable energy resource with solar collector as assisted heat. This is offered as a more efficient and faster alternative for composting of waste and better management of biodegradable residues.

Potential target audience of technology are households, households with farms, small-scale producers of bioproducts with residual biomass. Combining the state of art biogas production technology with the solar collectors (considering the price-performance ratio) can reduce probable costs of heating reactor. Later optimization performance and operation of a hybrid system can result in even greater energy savings when the solar heating system is used and at the given type of reactor to ensure a stable production of biogas throughout the year despite changing seasons (Balasubramaniyam et al., 2008; Vinoth Kumar & Kasturi Bai, 2008). System comprises of five major components: biomass – pre-treatment and feedstock, digestate, psychrophilic plug flow digester, solar collector unit, use of gas. (Fig. 1). Solar collector heat will heat the reactor, if unnecessary, for the heating of accumulator. If it is necessary firewood boiler can be used for heating the bioreactor.

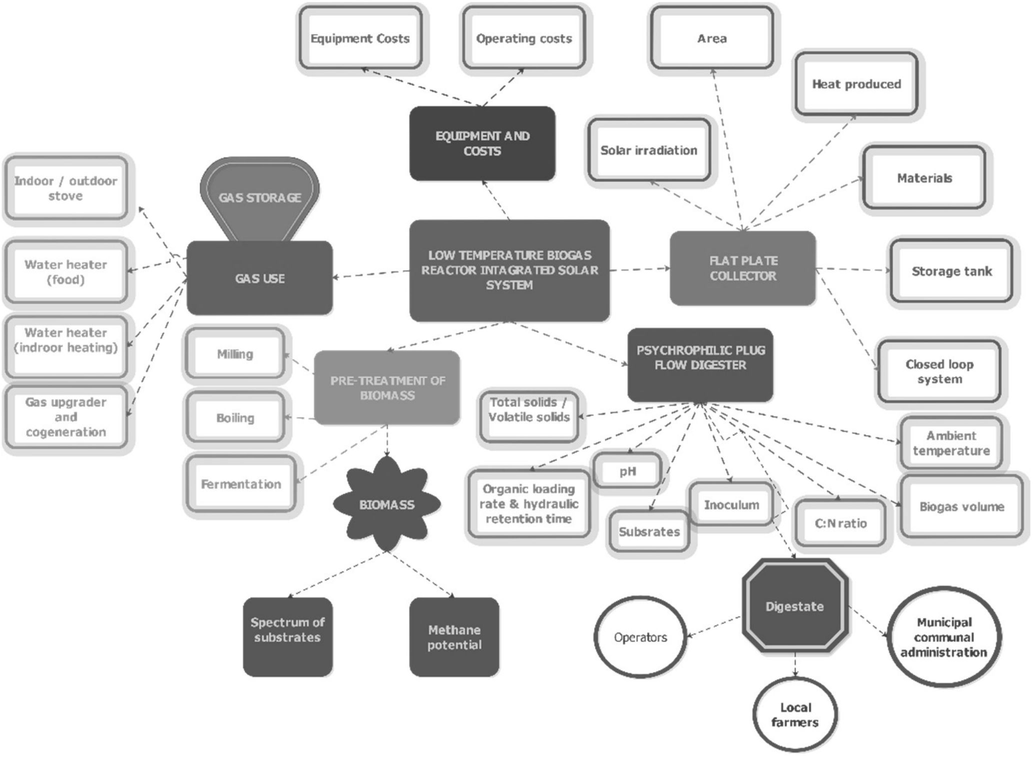

Figure 1. The framework of low-temperature biogas production system with integrated solar heat.

There are few reasons why we such hybrid-system must be supported. Solar heat-assisted biogas production is essential because a) almost everywhere in the world there are biomass and sun; b) solar heat energy Tian & Zhao, 2013; Suman et al., 2015), and anaerobic digestion of biomass (Mata-Alvarez et al., 2014; Hagos et al., 2017; Jingura & Kamusoko, 2017; Patil & Tathe, 2019) are sufficiently long studied technologies; c) technology can produce both heat and power, and fuel - this enables sector coupling (European Parliament, 2018). Additional consideration for the development of technology is that hybrid solar assisted biogas in the micro to small scale serves as a socio-economic integrator of renewable energy sources. It is also a driver of innovative renewable technologies (IRT) and helps the diffusion of knowledge about technologies by bottom-up integration, meaning community initiated and supported.

Solar heat will be used in several ways to assist the anaerobic digestion process, for pre-treatment of the feedstock, heating digester and reducing moisture in biogas produced. Several studies have been conducted on solar assisted biogas e.g. (Dai et al., 2007, 2009; Gupta, 2010a; Chamoli et al., 2011; Dong & Lu, 2013; Karimov & Abid, 2013; Nirunsin et al., 2017). Regional disparities in the availability and form of feedstock, solar intensity, serve as a barrier to technology transfer. Research is compulsory to facilitate the diversification of renewable energy and the development of hybrid systems for energy efficiency (Østergaard, 2012; Shahzad, 2012; Schaber, 2013; Soshinskaya, 2013; Lannoye, 2015). Development is needed in this topic to increase knowledge and later instinctively integrate technology in the regional renewable energy sector.

Multi-Locality of Biogas

Anaerobic digestion is complex and optimization is still ongoing, literature review shows that in the production and use of biogas there is no universal solution suitable for all interested parties. Temperature conditions, types and quantities of feedstock, economic situation, the level of education, vary regionally. Researchers agree that the biogas development and innovation process require an active network of heterogeneous peers (Muller & Peres, 2018). In addition, biogas policy is often national. Thus, there is a tendency to consider biogas as one homogeneous and a nationwide system but it is not. Over the years several technological styles have evolved and continue to operate. Production of biogas is because of various motivations. Technology transfer takes place, for example, between the farms, thus creating new opportunities for cooperation. With biorefineries, there is also an extension of the scope to include more participants and feedstocks. This means that biogas is not just one system as it is usually perceived but several local ones. Problem is that the politics of resilience are developed in such a way it has only one system - one type of production and one kind of use. Therefore, the benefits of diversity of technologies in the medium and long term are lost and hinder the development of the renewable energy industry. To increase biogas production, the diversity of biogas production needs to be recognized and promoted in the research and policy-making process. Diversification of production are essential factor for further development of the renewable energy industry. In the long term, in the European region, diversification of production would promote the flexibility of energy resources, moving towards regional energy autonomy (Shahzad, 2012; Olabi et al., 2015; Olsson & Fallde, 2015; Shmelev & Van Den Bergh, 2016).

Biogas producers and users are in a multi-local system. The authors use term multi-local (multilocality) to denote a variety of technologies, solutions, applications and scales of technology in a certain area or region. Development of biorefinery concepts will contribute to integration of biogas - the expansion of the scope, increase in a number of actors and feedstocks. Research that determines potential of gas production, technological and economic conditions are considered but are vaguely related to the social conditions. Thus, these studies can be very subjective in scientific sense and cannot be used as a basis for political decision making. Researchers should reckon with many technological styles to develop industry policies, research into biogas systems. (Almeida & Báscolo, 2006).

Development of renewable energy sector policies and support mechanisms require implementation of diversified biogas production, interdisciplinary and applicable scientific research including comprehensive (social) and sectoral (economic) preconditions. The potential for production and uses of biogas globally is very high. At the moment a tiny part of the available resources is used and it needs to be changed. Diversifying the production of biogas with the solar collector support system is a way to promote and improve biogas production and, overall, renewable energies in the region (Fig. 2) (Olsson & Fallde, 2015; Owen, 2018).

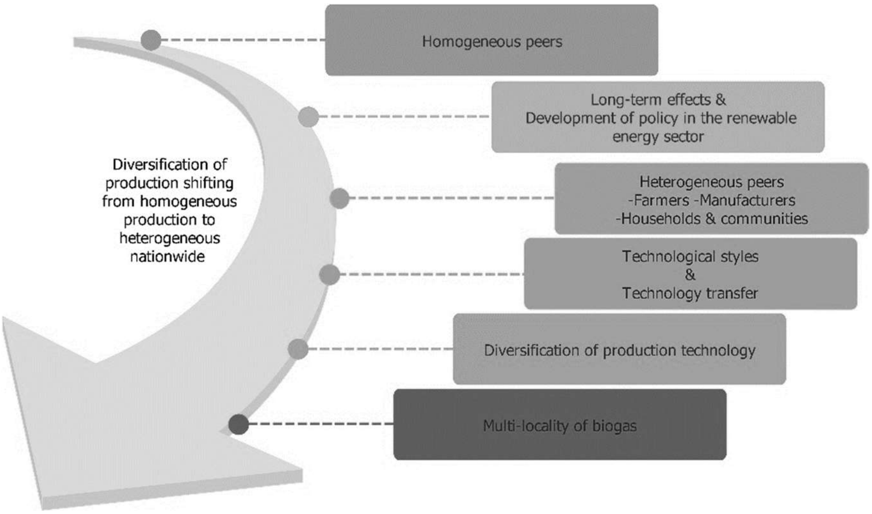

Figure 2. Diffusion of innovation for diversification and increase of biogas production.

Small-scale anaerobic digestion system with solar heat support - influencing factors and design investigation

Optimal performance of anaerobic digestion depends on several parameters. Various groups of bacteria are engaged in the production of methane and appropriate conditions must be created to ensure that all microorganisms are in balance. As the complexity of the process is high for anaerobic digestion factors affecting the yield of produced methane is quite large. Absolutely, the temperature matters in biogas production it substantially determines the activity of microorganisms, other key factors are C/N ratio, pH, blending, feedstock, *)*. Anaerobic digestion is a protracted process and the adaptation of microorganisms to a new state when the feedstock or temperature changes is about three weeks. Thus, it is essential to provide a more constant temperature and homogeneous easy to degrade feedstock. Vast majority of the hydrogen-consuming methanogens grow in of 6.7 to 7.5 pH, meaning the neutral pH is beneficial for biogas production. Acid-forming microorganisms grow under mesophilic conditions, but methanogens at higher temperatures. Mixing is also an important for biogas production, too much stresses bacteria and without mixing foam appears. Methane-producing microorganisms grow gradually, with a doubling time of about 5 to 16 days. Accordingly, the hydraulic retention time in the psychrophilic range should be at least 30–60 days. Also important is the feedstock used, its carbon balance with other nutrients, primarily nitrogen, and phosphorus and sulfur. Digestion needs to be done slowly in different circumstances easily disintegrated substrates can cause escalation in acid and inhibition of the process. The carbon to nitrogen proportion needed to be approximately 16:1 to 25:1. Too much carbon or nitrogen increase or decrease biogas production. The concentration of solids in the bioreactor should be between 7% and 14%. The size of the particle of the substrate is less important than temperature and pH. However, the size of the particles affects the rate of deterioration and ultimately generation rate of the biogas (Deublein & Steinhauser, 2010; Rajendran et al., 2012; Achinas et al., 2017).

Production of the most efficient biogas takes place in the co-fermentation mode with the addition of high carbon substrate to high nitrogen substrate. Depending on the location of the technology, the processing plant can choose a feedstock, for example, sewage treatment activated sludge, manure, plant biomass, silage, damaged fish feed, cereal products, and other food/feed residues can be used (Mata-Alvarez et al., 2014; Hagos et al., 2017). The psychrophilic reactor is more stable than mesophilic or thermophilic (Wei & Guo, 2018), and then the main control parameter is the pH value. When increasing the pH of the reactor, more raw materials with high carbon content should be added. The total dry matter content of the bioreactor should not be greater than 14% for plug flow digester. This reduces the energy consumption of the mixing system. Required dry matter content of the bioreactor is ensured by diluting feedstock with water. The main advantages of psychrophilic temperatures for anaerobic digestion would be the lower energy input required for heating the reactor, consequently reducing the overall operating cost. Most recent results on microbiological activity in psychrophilic conditions show that lower temperatures require a longer digestion time and lead to higher methane content and lower accumulation of volatile fatty acids compared to mesophilic conditions, although still keeping a similar cumulative biomethane yield in both conditions (Gruduls et al., 2017).

Main factors that influence heat produced by solar collector is intensity of sun, type of solar collector generation used, solar collector area, angle, position, height, the height of the surroundings, rotating and rotating rate, capacity, flow rate, material's thermal conductivity, color, insulating and consuming rate. Heat loss from the collector plate depends on several factors. Such as (1) absorption plate temperature, (2) spectral properties of the collector plate, including absorption and emission capacity, (3) air temperature; ambient air and sky conditions; (4) number and characteristics of glass panes and their spacing; (5) the physical properties of the heat for the insulation material used at the edges and at the back; (6) the horizontal inclination of the collector; and (7) the wind speed above the absorber (Garg & Rani, 1980).

When solar heat is produced there is a need for heat accumulation. There are few materials used as heat energy storage media, for example, sand-rock minerals, reinforced concrete, cast iron, salt (NaCl), cast steel, silica fire bricks. But the cheapest and most commonly used is water (Lázaro et al., 2009). Water has a high heat capacity (about 4,180 kJ $m^{-3} \cdot K^{-1}$) but is limited to 100 °C unless there is increased pressure. Most materials used for intelligent heat storage range from 900 to 3,000 kJ $m^{-3} \cdot K^{-1}$. Heat conductivity of the following materials ranges from 0.5 to 4 W $m^{-1} \cdot K^{-1}$ (Stutz et al., 2017). Main factors that ensure the technical feasibility of a solar thermal storage system are superb technical features. First, high sensible heat storage capacity is essential to reduce the volume and increase the efficiency of the system. Second, a good heat transfer rate should be maintained between the heat storage material and the heat transfer fluid to ensure that the heat energy can be released/absorbed at the desired rate. Third, the storage material should have good stability to avoid degradation (chemical or mechanical) by a specific number of thermal cycles. The cost of a solar thermal storage system consists mainly of three parts: storage material, heat exchanger and land costs. Cost efficiency is usually associated with technical characteristics. High heat storage power and exceptional heat transfer performance can substantially decrease the size of the system (Tian & Zhao, 2013).

To build a solar heating system for Latvia, weather data for specific location must be collected. First necessary to acquire data on the sun radiation (global, diffuse, and direct), other environmental factors, such as the outside temperature, the relative humidity of the atmosphere, and the wind speed. Due to temperate meteorological conditions, reactor outages are possible during winter when external heating are required, most likely, the break could be from the beginning of January to March. It should be mentioned that low temperature operation is mainly to avoid the need for electric heating of the reactor during the spring and autumn months, it also ensures a more stable process. Previous studies on solar energy and temperature in Latvia show that from 2015 to 2020 in Riga, Latvia yearly total solar radiance was 1,017 kWh m^{-2}. Planning for energy production rates and heat demand is quite challenging in due to the local climate. Trend indicates that weather in Latvia is erratic, for instance, the maximum ambient air temperature in 2020 was 30.8 °C, but by 2021, it had already risen to 37 °C in several parts of the country, the lowest ambient air temperature in 2020 was - 10.3 °C, but by 2021, - 31 °C (Polikarpova et al., 2021). Meteorological conditions, region, topography, season, daytime or night, changes vary considerably in different climatic conditions. When developing a solar system, to magnify the use of solar energy, it must be ensured that the system has high heat exchange efficiency and energy recovery. This requires a temperature control system to keep the temperature constant. Heat is stored to match temperature between day and night, sunny or cloudy (Ren et al., 2012).

It is necessary to achieve the most suitable solution for the solar heating component for the system (MPMSAA, 2009). The system contains a collector, a heat transfer control pool and a temperature control system. Solar energy is collected by collectors to heat media material for heat transfer. The heated transfer control pool is connected to the heating manifold through the pipelines. Pipelines in a heated transfer basin should be constructed as uniformly as possible to assist in heat transfer (if there is a larger pool, blenders are required). To reduce heat loss, the basin and pipe casing must be insulated. The temperature control system includes a temperature probe. The probe can keep track of the pool temperature and provide a timely response to the controller connected to the pump to control the amount of heat to reach the reaction temperature. Characteristics of the solar component are shown in Table 1.

Table 1. Characteristics of the bioreactor and solar components

Component	Detail
Digester type	Plug flow digester
Digester volume (for one household)	4 m^3 (2 m^3 to 15 m^3)
Length to width ratio	3.5:1
Process	Two-phase system
Gas collecting	The upper part of the digester or balloon
Portability	Portable
Operation	Semi-continuously
Hydraulic retention time	30–60 days
Solid content	7–14%
Digester temperature range	15–35 °C
Inoculum source	Wastewater treatment plant or cow manure
Digestion unit	Plastic
Feed tank	Metal with pre-treatment unit
Mixing	No
Digestate storage tank	Metal/concreate
Tubes	Plastic, insulated metal
Digester unit heating jacket	Metal tubes/wiring
Insulation	Composite material, rock or glass wool, organic - reed, or other
Feedstock	
Water source	Rainwater tank/underground
Heating source	No heating or solar collector/heat accumulator
Pre-treatment	Milling, boiling, chemical, drying
Co-substrates	Methane potential in volatile solids (VS) or total solids (TS)
Food waste (FW)	Co-digestion with other substrates was 0.27–0.86 m^3 CH_4 kg VS^{-1} (Bong et al., 2018)
Fish waste (FIW)	Biomethane production potential of 0.2 to 0.9 CH_4 m^3 kgVS^{-1} (Ivanovs et al., 2018; Bücker et al., 2020)
Garden waste (GW)	0.10 ± 0.02 biogas (m^3 kg^{-1} VS) [8], (Getahun et al., 2014)
Cow manure (CM)	0.6–0.8 m^3 kg^{-1} TS CH_4 g TS (Ferrer et al., 2011)
Slurry storage, organics content	Digestate storage tank, organics content after digestion is variable depending on reactor temperature and specific activity of microorganisms and other complex factors
Solar collector type	Flat plate collector
Solar irradiation, annual	950–1,050 kWh m^2
Flat plate collector, model	Optional
Gross area of collectors	20 m^3
Inclination angle to horizontal	34°
System type	Closed loop system
Oriental angle	0°, south
Storage tank	Cylindrical tank
Heat exchanger	Helical coil heat exchanger
Heat transfer fluid	Water + glycol (for freeze protection)
Collector interconnection	Parallel-connected collector array
Control systems	Pumps, controllers, temperature control
Portable	Yes
Solar heat application	Heating of water for different uses

Practice shows that a successful reactor must be capable of taking a sufficient amount of biomass. The reactor as microbiological growth and replication ecosystem of different micro-organisms must be stable, the flow of materials and energy smooth and efficient. It is problematic for a household to choose one appropriate type of digester. Design depends on geographic location, feedstock availability and climatic conditions and other circumstances. From all the distinct digesters, the dome developed by China and the floating drum developed by India continues to operate until today. Plug flow digesters gain attention because of ease of operation and portability (Rajendran et al., 2012). What materials will be used for the construction of the biogas digester depends on the local conditions – geological, hydrological, and locally available materials (Shian et al., 2003). In recent years, as a result of technological advances, there has been a proliferation of materials with improved properties and lower costs (Rajendran et al., 2012). For the construction of this type of digester stones and bricks are used as a building material. With the advancement of technology, PVC and polyethylene are used because they are comparatively inexpensive (An et al., 1997). From different materials used for the construction of mini-digesters most promising in the case of East Europe are bricks and concrete and plastic - polyvinyl chloride, polyethylene, with or without modifications. Main advantages of plastic are less weight, easily portable, relatively cheap, bricks and concrete have an advantage over maintenance cost and the material is everlasting. Disadvantages of plastic - relatively short life span, disadvantages of bricks and concrete - difficulty to clean, built underground, the possibility of gas escaping through concrete when pressure increases. As research in household biogas digesters shows the psychrophilic biogas reactor in its simplest form may be a plastic or concrete tank, in which anaerobic environments undergo degradation of organics and the formation of biomethane. The decision of the reactor elements is determined by the availability of materials and price. Smaller households or household communities are more suitable small-sized reactors that can be installed in the territory of household and run at ambient temperatures or with solar heating support. Larger farms are better suited for production capacities with concreted large-volume reactors that are insulated or partly below ground level to provide reactor operation in winter (Rajendran et al., 2012).

Biogas system comprises the following components:

- Pre-treatment tank consists of electrical miller - homogenizer and is used for the feedstock particle size reduction and mixing with water. Feedstock inlet comprises of a container for organic waste and a tube with a diameter of at least 10 cm;
- Psychrophilic anaerobic digester - organic waste reservoir in which the feedstock is degraded by anaerobic microorganisms to produce biogas;
- Gas storage/reservoir depending on the design can be just a room above the digester or a durable rubber balloon;
- Exhaust pipe is a tube of similar size with an inlet pipe connected to the surface at a slightly lower level than the intake pipe to facilitate digester discharge;
- Digestate storage is tank made from the impermeable layer for dehydration of digestate or storage;
- Gas burner - modified burner for cooking or water heating.

Digester design is adapted to the situational aspects outlined in this paper. Literature review shows it is possible to produce biogas in climates with cold winters (Balasubramaniyam et al., 2008; Gupta, 2010a). Our design is modified reference digester suggested by Adebayo et al. (Adebayo et al., 2014). To make the household digester attractive it must integrate features such as good maintenance capability, simple operation, relatively inexpensive design, using locally available materials. From the simple structure digesters, plug flow digesters best meet the criteria needed but also ensures its place to live acid and methanogenic producing bacteria. The inclined position produces a two-phase system making it possible to separate acidogenesis and methanogenesis longitudinally (Adebayo et al., 2014).

Characteristics of the bioreactor and solar components are shown in Table 1. It is possible that in some of the reactor components other materials can be used. It may be possible that some of the reactor components are not needed if it is found that during the construction of the prototype component is interfering with the system, easing system operation, and operational costs.

Technology has different potential applications, however, one example of the possible use of technology will be briefly described below. As declared in the above paragraphs the idea is suggested for household environments, on a larger or smaller scale with or without related production that generates biodegradable residues. Technology can be used, for example, a small producer of bio-based goods. This small producer which generates a variety of food products generates 47 tons of biodegradables a year. Generating 47 tons of waste means that daily production is up to 130 kg of food waste. Results show biomethane production in a low-temperature biogas reactor (average temperature 20 °C) has a retention time of 53 days, in a co-digestion mode, with a maximum bioreactor size of 14 m^3. Theoretical calculated *OLR* is 1.72 kg VS m^3 per day. Considering that plug flow digesters can withstand ORL up to 10 kg VS m^3 per day (Nathalie Bachmann, 2013). Therefore, the maximum size of the bioreactor is reduced three times to 4 m^3, with *OLR* 6.88 kg VS m^{-3} per day.

The average yield of biomethane in the co-digestion of food waste and activated sludge, at low temperatures with substrate retention of 28 days, is from 90 to 200 m^3 of CH_4 t^{-1} of food residue, depending on the type and water content (Chen et al., 2010; Rajendran et al., 2012; Zhang et al., 2014). The production unit of this size theoretically could produce an equivalent of ~20,000 m^3 of biogas a year if the biomass is digested with maximal efficiency. Depending on the feedstock used and its volatile solids, biomethane content it is from 4,230 m^3 to 14,800 m^3 a year (Table 2). In best case scenario, system of this size in the maximum effective mode would produce 27.5–96.2 MWh of heat per year. The thermal energy of the hybrid-system can be used for heating living and production premises, drying wood or food, sprouting grains, growing vegetables and mushrooms, growing insects, earthworms, and similar solutions.

Table 2. Characteristics of the technology studied

Characteristic	Value
Biomass quantity, annually	47,000 kg
Biomass volume, annually	~95 m^3
Biogas yield for food waste	0.4 m^3 kg TS^{-1}
Average FW feedstock density	510 kg per m^3
Reactor temperature, average	20 °C
Biomethane concentration in biogas	60%
Organic loading rate	6.88 kg VS $m^3 day^{-1}$
Hydraulic retention time	~53 days
Reactor size, m^3	4–15 m^3
Solar collector, area	20.2 m^2
Usable solar heat produced, year	~3,000 kW
The amount of biomethane produced	4,230–14,800 m^3 CH_4

Considering a small-scale the costs may vary depending on the type and quality of the selected materials and scale. The payback time for digester with solar collector, control system, heat storage, needs to be determined by market analysis of the offers, and it depends on the reactor, collector technology, heat accumulator capacity and increase of component price.

The importance of social approval for decentralized energy systems plays an important role for broad consumer use. Development of suggested renewable technology and modifications in the long term will make significant impact. Implementation of technologies will move industry towards a heterogeneous energy. In the long run it increases (1) energy resilience; (2) decreases the volatility of energy prices and the (3) introduction of a block-chain (market); (4) minimizes the environmental impact on human health by promoting industry connectivity to the integration of renewable energy. Linking electricity, heat, and transport to the infrastructure and stored energy carriers, could be achieved. It is necessary to develop decentralized systems because there are a large number of, for example, bioreactor owners, then the system is much more integrated - from supply to demand, and horizontally - between different energy vectors - electricity, heat, gas. Decentralized energy systems can reduce transmission costs and centralized energy capacity. At the current level of technology, fully autonomous regions are economically impossible due to the need for large energy storage capacities (Pierie et al., 2016; Anyaoku & Baroutian, 2018). Use of biogas as a renewable energy source will help to reduce negative external effects (emissions of CO_2, methane and thereby global warming, and polluted air, water, and soil) and by that reducing social costs of energy production. Biomethane as energy source gives positive overall economic effects - reduction of fossil energy import, saving of foreign exchange, less dependency upon foreign energy supply, less price volatility, improvement of electrical energy supply. Biogas as a renewable energy source is a good investment opportunity because planning, construction, and operation are not way too complicated. There will be good effects of increased biomass use. If waste biomass is used it will result in waste reduction, reduced costs of waste treatment, reduced environmental risks and groundwater pollution, unpleasant smell, health and sanitation problems. The exploitation of renewable energy produced from anaerobic digestion leads to direct and indirect benefits for the producer and the community - environmental benefits, improved living standards and revenue from sales of energy.

It is crucial to improve public awareness by introducing society to biogas production as an easy and convenient way to manage biodegradable residues. Development of household biogas may lead to community biogas as a way of treatment of biowaste and producing energy, and later probably a business. To ensure the regional investment potential of the energy sector, it is necessary to diversify renewable energy resources. And one way of doing this is to increase the share of biogas (biomethane) in the final energy consumption of renewable energy. The anaerobic digestion application rate for biodegradable waste management could be increased in two main ways. First, in the context of knowledge transfer by increasing the resonance of the biogas production on its extraction, use and positive aspects for society. Second, technologically - increasing the number of feedstocks used and diversifying technological solutions so that they are more widely available for households, companies, farms. Environmental and economic valuation of system will be carried out to estimate the cost of energy and the initial investment for this type of solution.

Kowalczyk-Juśko et al., 2019 analysed spatial and social conditions of agricultural biogas plants in Poland. More than 80% of respondents believe that the building of a biogas plant will help the commune by safeguarding the environment, providing people with cheaper power, and delivering cash to farmers by creating additional employment and crop sales. Concerns regarding the construction of biogas plants include unpleasant odors, loudness, increased pollution, and the possibility of an explosion. The size of the land on which the agricultural biogas plant will be built, as well as the condition of the roads, connectivity to the power grid, distances from possible substrate suppliers, and distances from human habitats, are all important considerations. Choosing the appropriate site entails taking into account a number of technological, legal, environmental, and social issues (Kowalczyk-Juśko et al., 2019).

Small-scale agricultural biogas facilities, geared to small amounts of feedstock and farm energy requirements, should become increasingly popular in Europe. The capacity provided in such units must be sufficient to cover the energy needs of one residence. Czubaszek et al., 2022 draws attention to careful calculations and correct recognition of the nature of feedstock and parameters in small biogas plants. According to technical considerations, the approach would lower the cost of modifying the reactor to the feedstock to be utilized. Small agricultural biogas plants' feeding systems might be more complicated, according to research. Due to the variable physical characteristics of the feedstock that the operators utilize, such stations need to be adaptable in terms of technology and equipment. Additional research is required to determine an affordable pre-treatment method that will improve the efficiency of anaerobic digestion in small reactors. (Czubaszek et al., 2022). For pilot plant development at temperate climate use mixture of psychrophilic and mesophilic bacteria are suggested (Jaimes-Estévez et al., 2020). According to the research findings of Prvulovic et al., 2022, based on the estimated energy requirements anaerobic digesters requires less energy from June to August, and more from November to March. An average of 16% of the generated combined heat and power engineheat is required yearly to heat the fermenter. Most thermal energy is required in January and December (20%), and the least in July (12%) (Prvulovic et al., 2022). Anaerobic digestion on a small scale is a promising method for treatment of organic part of municipal waste. It applies to the European agriculture industry, and adoption of installation is predicted to rise considerably (O'Connor et al., 2021).

CONCLUSIONS

This article concisely discusses the possibility of using a low-temperature biogas reactor with solar support as a management tool for household-to-small business biodegradable waste. Literature review confirms solar assistance to biogas increases production of biogas, efficiency of production, costs and decreases toxicity of digestate. Literature analysis highlighted the socio-economical value of technology in two contexts, a renewable technology reduce waste and produce energy and serves as bottom-up integrator of renewable energy, and that multilocality of biogas must be considered when the policy of the renewable energy sector is developed. Feasibility study shows that such small-scale systems can reduce the amount of greenhouse gases and contribute to progress towards the EU Green Deal. Design examination of a solar heat support was suggested in this paper to provide logical basis for further research.

Research is needed in different directions – socio-economic, identification of specific technical parameters of the workable system, defining size boundaries of hybrid system, sourcing of feedstock.

REFERENCES

Achinas, S., Achinas, V. & Euverink, G.J.W., 2017. A Technological Overview of Biogas Production from Biowaste. *Engineering* **3**, 299–307. doi:10.1016/J.ENG.2017.03.002

Adebayo, A.O., Jekayinfa, S.O., Akinloye, O.V., Babalola, A.M. & Usman, F.O. 2014. Design, Construction and Testing of a Plug Flow Digester for Converting Agricultural Residues to Biogas. *International Research Journal on Engineering* **2**, 52–60.

Agarkar, B.D. & Barve, S.B. 2011. A Review on Hybrid solar/wind/ hydro power generation system. *International Journal of Current Engineering and Technology* **4**, 3–7. doi:10.14741/Ijcet/22774106/spl.4.2016.38

Alkhamis, T.M., El-khazali, R., Kablan, M.M. & Alhusein, M.A. 2000. Heating of a biogas reactor using a solar energy system with temperature control unit. *Solar Energy* **69**, 239–247. doi:10.1016/S0038-092X(00)00068-2

Almeida, C. & Báscolo, E., 2006. Use of research results in policy decision-making, formulation, and implementation: a review of the literature. *Cadernos de Saúde Pública* **22**, S7–S19. doi:10.1590/s0102-311x2006001300002

An, B.X., Rodriguez, J., Sarwatt, S., Preston, T. & Dolherg, F. 1997. Installation and performance of low-cost polyethylene tube biodigesters on small-scale farms. *World Animal Review* **88**, 38–47.

Anyaoku, C.C. & Baroutian, S. 2018. Decentralized anaerobic digestion systems for increased utilization of biogas from municipal solid waste. *Renewable and Sustainable Energy Reviews* **90**, 982–991. doi:10.1016/j.rser.2018.03.009

Balasubramaniyam, U., Zisengwe, L.S., Meriggi, N. & Buysman, E. 2008. *Biogas production in climates with long cold winters*. Wageningen University, Netherlands. 68.

Bong, C.P.C., Lim, L.Y., Lee, C.T., Klemeš, J.J., Ho, C.S. & Ho, W.S. 2018. The characterisation and treatment of food waste for improvement of biogas production during anaerobic digestion - A review. *Journal of Cleaner Production* **172**, 1545–1558. doi:10.1016/J.JCLEPRO.2017.10.199

Bruno, J.C., Ortega-López, V. & Coronas, A. 2009. Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: Case study of a sewage treatment plant. *Applied Energy* **86**, 837–847. doi:10.1016/j.apenergy.2008.08.007

Bücker, F., Marder, M., Peiter, M.R., Lehn, D.N. & Esquerdo, V.M., Antonio de Almeida Pinto, L. & Konrad, O. 2020. Fish waste: An efficient alternative to biogas and methane production in an anaerobic mono-digestion system. *Renewable Energy* **147**, 798–805. doi:10.1016/j.renene.2019.08.140

Chamoli, S., Patil, A. & Saini, J.S., 2011. Parametric Optimization of Solar Assisted Bioreactor. *International Journal of Energy Science* **1**, 125–130.

Chen, X., Romano, R.T. & Zhang, R. 2010. Anaerobic digestion of food wastes for biogas production. *International Journal of Agricultural and Biological Engineering* **3**, 61–72. doi:10.3965/j.issn.1934-6344.2010.04.061-072

Czubaszek, R., Wysocka-Czubaszek, A. & Banaszuk, P. 2022. Importance of Feedstock in a Small-Scale Agricultural Biogas Plant. *Energies* **15**, 7749. doi.org:10.3390/en15207749

Dai, R., Chun, C., Xu, Z., Liu, X., Wang, Z., Solar, H. & Group, E. 2007. Application of Solar Heating System in Biogas Production. *Proceedings of ISES Solar World Congress 2007: Solar Energy and Human Settlement* 956–960. doi:10.1007/978-3-540-75997-3

Deublein, D. & Steinhauser, A. 2010. Biogas from Waste and Renewable Resources. Second edition. Wiley-VCH Verlag GmbH & Co. 550. doi: 10.1002/9783527632794

Dong, F. & Lu, J. 2013. Using solar energy to enhance biogas production from livestock residue - A case study of the Tongren biogas engineering pig farm in South China. *Energy* **57**, 759–765. doi:10.1016/j.energy.2013.05.046

European Parliament, 2018. Sector coupling: how can it be enhanced in the EU to foster grid stability and decarbonise? 64.

Ferrer, I., Garfí, M., Uggetti, E., Ferrer-Martí, L., Calderon, A. & Velo, E. 2011. Biogas production in low-cost household digesters at the Peruvian Andes. *Biomass and Bioenergy* **35**, 1668–1674. doi.org:10.1016/j.biombioe.2010.12.036

Filho, W., Ţîrcă, D-M., de brito, P. & Lima, I. 2018. Towards a Sustainable Bioeconomy: Principles, Challenges and Perspectives. *Springer International Publishing AG*. **554**. doi.org/10.1007/978-3-319-73028-8

Garg, H.P. & Rani, U. 1980. Loss coefficients from solar flat-plate collectors. *Applied Energy* **7**, 109–117. doi.org: 10.1016/0306-2619(80)90052-5

Getahun, T., Gebrehiwot, M., Ambelu, A., Van Gerven, T. & Van Der Bruggen, B. 2014. The potential of biogas production from municipal solid waste in a tropical climate. *Environmental Monitoring and Assessment* **186**, 4637–4646. doi.org:10.1007/s10661-014-3727-4

Gruduls, A., Balina, K., Ivanovs, K. & Romagnoli, F. 2017. Low temperature BMP tests using fish waste from invasive Round goby of the Baltic Sea. *Agronomy Research* **16**(2), 398–409.

Gupta, A. 2010a. Design of Solar Assisted Community Biogas Plant. *ASME 2009 3rd International Conference on Energy Sustainability collocated with the Heat Transfer and InterPACK09 Conferences* 475–480. doi.org:10.1115/es2009-90112

Gupta, P., Singh, R.S., Sachan, A., Vidyarthi, A.S. & Gupta, A. 2012. Study on biogas production by anaerobic digestion of garden-waste. *Fuel* **95**, 495–498. doi.org:10.1016/J.FUEL.2011.11.006

Hagos, K., Zong, J., Li, D., Liu, C. & Lu, X., 2017. Anaerobic co-digestion process for biogas production: Progress, challenges and perspectives. *Renewable and Sustainable Energy Reviews* **76**, 1485–1496. doi.org:10.1016/j.rser.2016.11.184

Ivanovs, K., Spalvins, K. & Blumberga, D. 2018. Approach for modelling anaerobic digestion processes of fish waste. *Energy Procedia* **147**, 390–396. doi.org:10.1016/J.EGYPRO.2018.07.108

Jaimes-Estévez, J., Zafra, G., Martí-Herrero, J., Pelaz, G., Morán, A., Puentes, A., Gomez, C., Castro, L. del P. & scalante Hernández, H., 2020. Psychrophilic Full Scale Tubular Digester Operating over Eight Years: Complete Performance Evaluation and Microbiological Population. *Energies* **14**, 151. doi.org:10.3390/en14010151

Jakobsons, M. 2015. *Solar collectors ' performance*. Master thesis. Norwegian University of Science and Technology. 194 pp.

Jingura, R.M. & Kamusoko, R. 2017. Methods for determination of biomethane potential of feedstocks: a review. *Biofuel Research Journal* **4**, 573–586. doi.org:10.18331/BRJ2017.4.2.3

Karimov, K.S. & Abid, M. 2013. Solar Biogas Digester with Built-In Reverse Absorber Heater., *Mehran University Research Journal of Engineering & Technology* **32**, 39–46.

Khoiyangbam, R.S., Gupta, N. & Kumar, S. 2014. Biogas Technology: towards sustainable development. First edition. TERI Press The Energy and Resources Institute Darbari Seth Block IHC Complex Lodhi Road, New Delhi. ISBN: 978-81-7993-404-3

Korres, N.E., Kiely, P.O., Jonathan, S.W. & Benzie, J.A.H. 2013. Bioenergy Anaerobic by Digestion and wastes: Using agricultural biomass and organic wastes, Routledge, Taylor & Frncis Group. doi.org/10.4324/978020313769

Kowalczyk-Juśko, A., Listosz, A. & Flisiak, M. 2019. Spatial and social conditions for the location of agricultural biogas plants in Poland (case study). *E3S Web Conf. 86, 00036*. doi.org:10.1051/e3sconf/20198600036

Lannoye, E. 2015. Renewable energy integration: Practical management of variability, uncertainty, and flexibility in power grids, *IEEE Power and Energy Magazine*. doi.org:10.1109/MPE.2015.2458758

Lázaro, A., Dolado, P., Gil, A., Zalba, B., Cabeza, L.F., Medrano, M. & Martorell, I. 2009. State of the art on high temperature thermal energy storage for power generation. Part 1-Concepts, materials and modellization. *Renewable and Sustainable Energy Reviews* **14**, 31–55. doi.org:10.1016/j.rser.2009.07.035

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M.S., Fonoll, X., Peces, M. & Astals, S. 2014. A critical review on anaerobic co-digestion achievements between 2010 and 2013. *Renewable and Sustainable Energy Reviews* **36**, 412–427. doi.org:10.1016/j.rser.2014.04.039

Mccabe, B.K. & Schmidt, T. 2018. Integrated Biogas Systems: Local applications of anaerobic digestion towards integrated sustainable solutions. *IEA Bioenergy Task*, 28–37.

Miltner, M., Makaruk, A. & Harasek, M. 2017. Review on available biogas upgrading technologies and innovations towards advanced solutions. *Journal of Cleaner Production* **161**, 1329–1337. doi.org:10.1016/j.jclepro.2017.06.045

MPMSAA, S. 2009. Large Scale Solar Thermal Systems Design Handbook. 127.

Mshandete, A., Kivaisi, A., Rubindamayugi, M. & Mattiasson, B. 2004. Anaerobic batch co-digestion of sisal pulp and fish wastes. *Bioresource Technology* **95**, 19–24. doi.org:10.1016/j.biortech.2004.01.011

Muller, E. & Peres, R. 2018. The effect of social networks structure on innovation performance: A review and directions for research. *International Journal of Research in Marketing* **36**, 3–19. doi.org:10.1016/j.ijresmar.2018.05.003

Nathalie Bachmann, E.S.A. 2013. Design and engineering of biogas plants. *The Biogas Handbook: Science, Production and Applications* 191–211. doi.org:10.1533/9780857097415.2.191

Nirunsin, R., Setthapun, W., Dussadee, N. & Ninsonti, H. 2017. Enhancement of household biogas production by solar collector and solar greenhouse. *International Journal of Renewable Energy* **12**, 103–115.

Nnali, K.E. & Oke, A.O. 2013. The utilization of fish and fish farm wastes in biogas production: “a review”. Advances in Agriculture. *Sciences and Engineering Research* **3**, 657–667.

O’Connor, S., Ehimen, E., Pillai, S.C., Black, A., Tormey, D. & Bartlett, J. 2021. Biogas production from small-scale anaerobic digestion plants on European farms. *Renewable and Sustainable Energy Reviews* **139**, 110580. doi.org:10.1016/j.rser.2020.110580

Olabi, A.G., Nkem-Ekpeni, F., Ekpeni, L.E.N., Benyounis, K.Y. & Stokes, J. 2015. Energy Diversity through Renewable Energy Source (RES) – A Case Study of Biomass. *Energy Procedia* **61**, 1740–1747. doi.org:10.1016/j.egypro.2014.12.202

Olsson, L. & Fallde, M. 2015. Waste(d) potential: a socio-technical analysis of biogas production and use in Sweden. *Journal of Cleaner Production* **98**, 107–115. doi.org:10.1016/j.jclepro.2014.02.015

Omer, A. 2018. Biogas Technology for Sustainable Energy Generation: Development and Perspectives. *MOJ Applied Bionics and Biomechanics* **1**, 137–148. doi.org:10.15406/mojabb.2017.01.00022

Østergaard, P.A. 2012. Comparing electricity, heat and biogas storages’ impacts on renewable energy integration. *Energy* **37**, 255–262. doi.org:10.1016/j.energy.2011.11.039

Owen, P.W. 2018. Sp*ecial Report Renewable energy for sustainable rural development: significant potential synergies, but mostly unrealised* **287**, 93.

Patil, P.D. & Tathe, D. 2019. Biogas production from kitchen waste : a review. 0–3.

Pierie, F., Bekkering, J., Benders, R.M.J., van Gemert, W.J.T. & Moll, H.C. 2016. A new approach for measuring the environmental sustainability of renewable energy production systems: Focused on the modelling of green gas production pathways. *Applied Energy* **162**, 131–138. doi.org:10.1016/j.apenergy.2015.10.037

Polikarpova, I., Kakis, R., Pakere, I & Blumberga, D. 2021. Optimizing Large-Scale Solar Field Efficiency: Latvia Case Study. *Energies* **14**, 4171. doi.org/10.3390/en14144171

Prvulovic, S., Josimovic, M., Radosav, D., Tolmac, J., Jovanovic, S. & Micic, I. 2022. Determining the thermal energy required to heat a biogas plant fermenter. *Material Tehnology* **56**. doi.org:10.17222/mit.2021.304

Rajendran, K., Aslanzadeh, S. & Taherzadeh, M.J. 2012. Household biogas digesters-A review, *Energies*. doi.org:10.3390/en5082911

Ren, Z., Chen, Z., Hou, L., Wang, W. & Xiong, K. 2012. Design investigation of a solar energy heating system for anaerobic sewage treatment. **14**, 255–259. doi.org:10.1016/j.egypro.2011.12.926

Schaber, K. 2013. *Integration of Variable Renewable Energies in the European Power System: A Model-Based Analysis of Transmission Grid Extensions and Energy Sector Coupling*. PhD Thesis, Lehrstuhl für Energiewirtschaft und Anwendungstechnik, Technische Universität München, München., 199 pp.

Seadi, T.A., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. & Janssen, R. 2008. *Biogas Handbook*, Igarss 2014. doi.org:10.1533/9780857097415.1.85

Shahzad, U. 2012. The Need For Renewable Energy Sources. *International Journal of Information Technology and Electrical Engineering*, pp. 16–18.

Shian, S.-T., Chang, M.-C., Ye, Y.-T. & Chang, W. 2003. The construction of simple biogas digesters in the province of Szechwan, China. *Agricultural Wastes* **1**, 247–258. doi.org/10.1016/0141-4607(79)90009-x

Shmelev, S.E. & Van Den Bergh, J.C.J.M. 2016. Optimal diversity of renewable energy alternatives under multiple criteria: An application to the UK. *Renewable and Sustainable Energy Reviews* **60**, 679–691. doi.org:10.1016/j.rser.2016.01.100

Soshinskaya, M. 2013. *Integrating Renewable Energy Resources: a microgrid case study of a Dutch drink water treatment plant*. Master thesis. Utrecht University. 93.

Stutz, B., Le Pierres, N., Kuznik, F., Johannes, K., Palomo Del Barrio, E., Bédécarrats, J.P., Gibout, S., Marty, P., Zalewski, L., Soto, J., Mazet, N., Olives, R., Bezian, J.J. & Minh, D.P. 2017. Stockage thermique de l'énergie solaire. *Comptes Rendus Physique* **18**, 401–414. doi.org:10.1016/j.crhy.2017.09.008 (in French)

Su, Y., Tian, R. & Yang, X.H., 2011. Research and analysis of solar heating biogas fermentation system. *Procedia Environmental Sciences* **11**, 1386–1391. doi.org:10.1016/j.proenv.2011.12.208

Suman, S., Khan, M.K. & Pathak, M. 2015. Performance enhancement of solar collectors - A review. *Renewable and Sustainable Energy Reviews* **49**, 192–210. doi.org:10.1016/j.rser.2015.04.087

Tian, Y. & Zhao, C.Y. 2013. A review of solar collectors and thermal energy storage in solar thermal applications. *Applied Energy* **104**, 538–553. doi.org:10.1016/j.apenergy.2012.11.051

Venkata Mohan, S., Nikhil, G.N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M.V, Naresh Kumar, A. & Sarkar, O. 2016. Waste Biorefinery Models Towards Sustainable Bioeconomy: Critical Review and Future Perspectives. *Bioresource Technology* **215**, 2–12. doi:10.1016/j.biortech.2016.03.130

Vinoth Kumar, K. & Kasturi Bai, R., 2008. Solar greenhouse assisted biogas plant in hilly region - A field study. *Solar Energy* **82**, 911–917. doi.org:10.1016/j.solener.2008.03.005

Wei, S. & Guo, Y. 2018. Comparative study of reactor performance and microbial community in psychrophilic and mesophilic biogas digesters under solid state condition. *Journal of Bioscience and Bioengineering* **125**, 543–551. doi:10.1016/j.jbiosc.2017.12.001

Wellinger, A., Murphy, J. & Baxter, D. 2013. *The Biogas Handbook: Science, Production and Applications*. Woodhead Publishing. 476 pp. doi.org:10.1533/9780857097415

Zhang, C., Su, H., Baeyens, J. & Tan, T. 2014. Reviewing the anaerobic digestion of food waste for biogas production. *Renewable and Sustainable Energy Reviews* **38**, 383–392. doi.org:10.1016/j.rser.2014.05.038

Zijdemans, D. 2012. *Vannbaserte oppvarmings- og kjølesystemer*. Skarland Press AS. 456 pp. (in Norwegian).