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IOT AND VIRTUAL POWER PLANTS

An overview of suitable technologies

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ABSTRACT

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The growing need for clean and sustainable energy, the integration of virtual power plants (VPPs) within the biogas plant framework represents a beacon of hope toward intelligent energy management. By enabling IoT solutions, the biogas plant potential will be upgraded to a smart and automated workflow resulting in less dependency on fossil fuel and more efficiency and resilience.

This thesis examines the role of IoT in enhancing the VPP workflow and energy monitoring. The goal is to explore different IoT solutions including electricity consumption meters, temperature sensors, wind speed sensors, and sunlight intensity sensors, evaluating their suitability for real-time monitoring. These solutions will go through a comparative analysis based on accuracy, data transmission methods, power consumption, EU regulatory compliance, and cost-effectiveness to identify the most suitable IoT solutions for the biogas plant VPP.

The research methodology is based on extensive literature review, devices datasheets, and an expert interview with the project manager carried out in order to identify the selection criteria. The goal of this study is to identify the right IoT solutions for energy monitoring and management for a real-world biogas plant. The findings of this thesis will serve as a technical reference for selecting and purchasing the right IoT hardware and software solutions that aligns the best with the given criteria, and the EU standards in general.

Key words

Biogas plant, Communication protocols, Energy meters, Energy monitoring, Industrial IoT solution, Internet of things (IoT), Sata transmission, SCADA, Smart grid s, Smart sensors, Virtual power plant (VPP).

CONCEPT DEFINITIONS

Internet of things (IoT): refers to a large, interconnected network of computer device such as sensors which exchange a huge amount of data rapidly. (Verma 2021, 2).

Virtual power plant: VPP is a cloud-based system that used for remote control various decentralised energy resources (DERs) biogas for example. the usage of the VPP can be seen in power optimization, and the smart grid system enhancement. (Yoldas, Ozturk, Senthilkumar, Kumar & Bogdanovic 2019.)

Biogas plant: is a facility that use agriculture waste, manure, or energy crops to produce methane rich biogas. This system is seen as a solution towards more sustainable waste management and less dependence on fossil fuel. (Ahmad, Banat, Taher, Khan & Baroutian 2022.)

Smart sensors: this term refers to the sensors that combine sensing, signal processing, and communication abilities in one device making it ideal for autonomous decision making and data transmission without human interaction. (Weber, Becker & Speck 1996)

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1 INTRODUCTION

The world's growing need for sustainable energy sources has led to increasing interest in Virtual Power Plants (VPPs) as a decentralized and intelligent energy management solution. A VPP integrates multiple distributed energy resources (DERs), including biogas plants, solar panels, wind farms, and battery storage systems, into a digitally controlled platform that optimizes energy production and distribution. By integrating Internet of Things (IoT) technology, VPPs provide real-time energy monitoring, automation, and grid balancing thus improving the dependability and efficiency of renewable energy sources.

Biogas plants, a key component of renewable energy infrastructure, primarily produce methane and carbon dioxide through the anaerobic digestion of biodegradable organic materials such as biowaste, sludge, manure, agricultural residues, and energy crops. These plants not only serve as an effective waste management solution but also provide an alternative energy source, reducing dependence on fossil fuels for power generation, heat production, and even vehicle fuel conversion. Biogas production is particularly valuable in agriculture, offering European farmers a sustainable, local energy source that decreases fossil fuel consumption and contributes to energy self-sufficiency. (Ahlberg-Eliasson, Nadeau, Levén, Schnürer 2017,1-2).

However, integrating biogas plants into a Virtual Power Plant (VPP) requires continuous monitoring of various parameters, such as electricity consumption, temperature, and environmental conditions. Traditional biogas plant monitoring systems rely on manual inspections and periodic data logging, which creates room for transcription errors, delays in responses, and higher operational costs, making the process inefficient. This inefficiency highlights the need for real-time data updates, automation, and remote energy management, all of which can be enabled through IoT-based VPP integration.

IoT-based monitoring and automation technologies provide a solution by enabling real-time energy tracking, predictive maintenance, and secure data communication. A VPP consists of four fundamental components that facilitate power flow operations: distributed energy resources, energy storage systems, controllable loads, and information and communication technologies (Swami, Saini, Suthar, Komal, Addula& Lande 2024, 2). Using the right IoT devices to monitor the complete chain of processes, from the implementation of biogas plants to biogas production and utilization, has proven crucial for achieving sustainable outcomes allowing biogas plants to be monitored remotely, respond dynamically to energy demand, and integrate efficiently into VPPs.

This thesis explores the role of IoT in optimizing Virtual Power Plant (VPP) operations with a specific focus on biogas energy monitoring. It examines the different IoT technologies used in energy monitoring across various aspects, including electricity consumption meters, temperature sensors, wind speed sensors, and sunlight intensity sensors evaluating their suitability for real-time monitoring. The study objective is to also compare suitable IoT solutions to identify the most effective in directly measuring and processing values or reading from existing energy meters of a biogas plant according to the given criteria (accuracy, cost-effectiveness, power consumption). Additionally, the research will analyse data storage and transmission methods, ensuring compatibility with modern ICT solutions and VPP requirements.

Further, this thesis will examine EU standards and cybersecurity protocols that IoT devices must comply with in energy systems, addressing potential risks related to data security, authentication, and secure communication. The findings of this research will serve as a technical reference for selecting market-ready IoT hardware and software solutions that enable efficient energy monitoring and enhancing the performance of biogas plants within a Virtual Power Plant framework.

2 IOT TECHNOLOGIES OVERVIEW

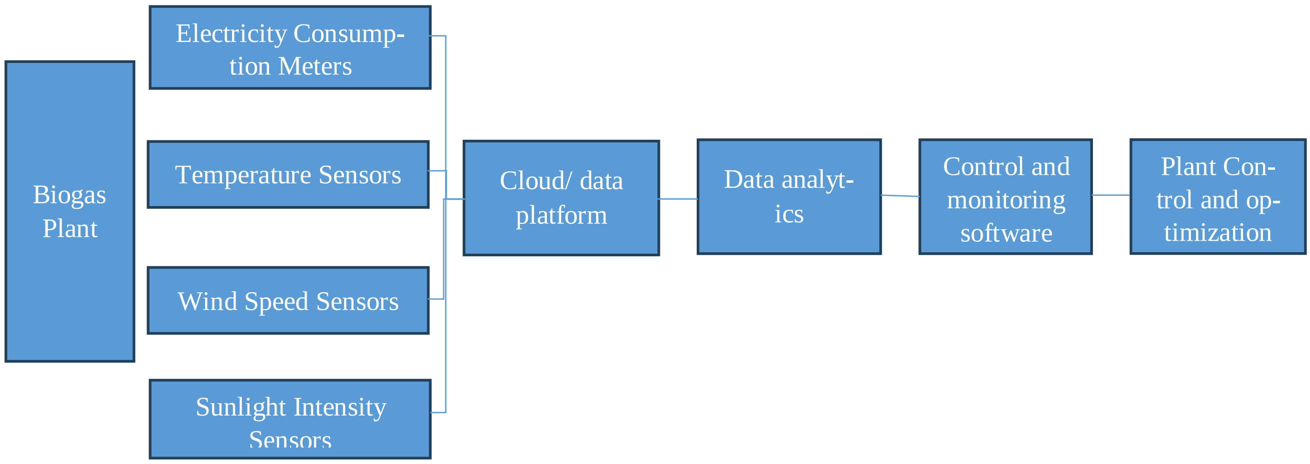
This chapter presents various IoT technology applications for energy monitoring, using diagrams to illustrate the virtual power plant (VPP) workflow within the context of a biogas plant. This section will also discuss some real-life projects within the EU as life examples of using these technologies in current projects. This section will also dive into the selection criteria for these IoT devices through the interview with the project manager where he highlights the main focus points that the suggested IoT solution must align with. Table 1 was used to demonstrate these different criteria discussed in the interview for an easier viewing experience and seamless understanding.

2.1 Current IoT Applications in Energy Monitoring

The integration of IoT has transformed numerous industries by enabling automation and enhancing operational efficiency. In the energy sector, IoT plays a foundational role in improving monitoring, performance, and decision-making. A biogas plant generates energy by converting organic waste into biogas, which is then used to power generators or combined heat and power (CHP) units. Within a virtual power plant (VPP) architecture, biogas plants contribute consistent energy production and serve as backup sources when other renewable energy sources, such as solar or wind, experience generation issues (Kumar, Baredar & Shukla 2018, 1).

To facilitate monitoring and real-time data collection, IoT sensors—such as temperature, wind speed, and sunlight sensors—are deployed in biogas plants. These sensors gather critical operational data, which is transmitted to a cloud-based VPP management system. This system forecasts future energy output, enhances energy planning, and optimizes distribution to ensure efficient flow within the grid. Additionally, it enables remote monitoring and automated adjustments, reducing operational costs and improving overall plant performance (Sawami et al. 2024, 1–2).

Figure 1: Sensor-to-cloud communication process in a biogas plant (Adapted from Swami et al. 2024, 3).



As shown in figure 1, an IoT based biogas plant monitoring workflow it starts by generating data from energy metre and other different other sensors. Using IoT gateways (e.g., Advantech WISE-6610) the data is collected and then transformed to cloud platforms (e.g., AWS IoT Core) which then store and analyse real-time energy data. The results of this data analytics are then used to improve the cycle using automated control systems, Siemens S7-1200 PLC for example to adjust energy flow, load balancing and system efficiency so that finally the VPP platform optimizes energy distribution ensuring biogas power is used or sold efficiently. (Sawami el al. 2024, 2.)

In today's world, the application of IoT in biogas plants has become an increasingly common practice in several countries, especially within the European Union (EU), thanks to its cutting-edge advancements in automation and remote control, leading to highly efficient outcomes. The EU is considered a global leader in biogas production, with Germany, the United Kingdom, Italy, Spain, and France being the top producers in Europe. In 2017, the European Biomass Association (EBA) estimated that the EU's realistic biogas production capacity was approximately 465 TWh, equivalent to 40 million tonnes of fossil fuels. (Wang, Littlewood & Murphy 2018.1-2.)

These initiatives frequently depend on IoT to monitor contemporary biogas plants and Virtual Power Plant (VPP) networks, resulting in better energy distribution and more efficient operations. Another significant example is the Next Kraftwerke Virtual Power Plant (VPP) in Germany, according to the project official website. Next Kraftwerke VPP is using IoT smart meters and predictive analytics have been incorporated into the VPP framework to increase the integration of biogas plants into smart grids. This implementation allows for real-time monitoring and dynamic energy management. The goal of this project is to connect separated energy resources (wind farms, solar parks, and CHP units) to monitor, predict, optimize, and enhance the electricity trading. (Next Kraftwerke, 2025.)

2.2 Criteria for IoT Solution Selection

In order to ensure that the selected devices align with the project needs and overview, an interview has taken place with the project manager where several questions have been answered concerning the selection criteria that need to be considered in the selection process, these questions are listed in appendix 1. The interview has covered different aspects such as the accuracy, data collection frequency, installation environment, communication & integration, communication protocol, security & guidelines, budget & costs, maintenance, and potential future expansion. All these discussed criteria are summarized in the following table based on the answers given by the project manager in each regard.

Table2: Requirement and criteria of IoT hardware

Criteria	Requirements & Considerations
Accuracy and Precision	Acceptable range: **±1–2%** deviation. The less the better
Data Collection Frequency	Real-time data is not required, but updates should not exceed the 1–5 minutes time window.
Installation Environment	Outdoor devices such as wind sensors need to be weather-resistant.
Communication & Integration	Modbus is preferred but not mandatory. Devices can use LoRa, Wi-Fi, or wired connections depending on feasibility and distance.
Data Communication Protocol	MQTT, HTTP, OPC UA.
Security & Compliance	Devices must comply with EU regulations. Devices without CE certification should be avoided. Data storage must be within the EU if using cloud-based solutions.

Budget Constraints	Total IoT budget: ~€7,200 for sensors & monitoring tools. Energy meter cost limit: Ideally under €1,000 per unit.
Maintenance & Support	Centria team is responsible for maintenance. If factory calibration is required, devices will be sent back for servicing
Future Expansion	Devices should allow for future system expansion.

Table 1 shows that the ideal IoT device offers high accuracy, frequent data updates, easy integration, affordability, and flexibility for future expansion. These criteria will play a crucial role in the decision making considering the right IoT solution for the biogas plant. The following section will go through a comparison of different devices and sensors resulting to the selection of the suitable devices for a seamless integration into the biogas plant's VPP framework.

3 IOT DEVICES FOR ENERGY MONITORING

Energy monitoring in one of the main parts of the VPP workflow within a biogas plant framework. It mainly has to do with collection and monitoring data from different meters or sensors throughout the grade. In this section the focus will be on creating an overview and an understanding on these different meters and sensors selecting devices according to the given criteria in table 1 and putting all the selected devices in each category into comparison analytics in order to help determine which is the right fit in every category. The goal of this chapter is to find the best IoT solutions (meters, sensors) for energy monitoring and identify the reason behind each selected device.

3.1 Smart Energy Metering Systems

Smart Energy metering systems (SEMS) refers to electric devices that contains an energy meter chip making it capable of measuring energy consumption and data communication by utilizing wireless protocol and additional devices for security, data display, and meter control, among other purposes. While traditional energy consumption meters relay more on manual control making it inefficient on many aspects, including IoT in SEMS enabled real-time communication of electrical failure for a quick repair. The main advantage that SEMS has to offer has to do with their ability to alert users when power consumption exceeds a preselected value. SEMS also provide a real-time or near real-time electricity rates and pricing insights, facilitating the decision making regarding the energy consumption relying on data analytics. (Dahunsi, Eniola, Ponnle, Agbolade, Udekwe & Melodi 2021, 71.)

According to Dahunsi et al. (2021, 72), Smart Energy Management Systems (SEMS) started gaining widespread use around 2008 as an upgrade to traditional analog electricity meters. These analog meters were limited to manual or local measurements and lacked the capability for real-time data transmission. As a result, they could not support remote monitoring, which is a key feature in modern energy systems. SEMS introduced digital functionality that enabled real-time data collection and improved energy tracking. Despite this advancement, many households still use basic digital meters without IoT integration. These meters typically resemble the older electromechanical models, offering limited capabilities. Without connectivity, they do not support automated energy management or remote access.

Figure 2 depicts the process of the Smart Energy Metering System. The procedure starts with real-time measurements of consumption, voltage, current, and power. Depending on the devices utilized, the system can directly measure or read these numbers from existing energy meters. The data is then communicated via an IoT Gateway, also known as the Data Transmission Unit. This gateway connects the energy meters to the cloud server, translating gathered data into IoT-compatible formats as MQTT, HTTP, or OPC UA. It secures data connection using encryption and authentication techniques. In the third step, the transmitted data is stored in a cloud-based database, where it is processed and analysed to identify patterns and optimize power usage. This enables remote monitoring and the generation of automated reports for plant operators. The analysed data is then visualized on a user-friendly interface, providing real-time energy insights. Finally, the grid or load management system receives the processed data and reports, facilitating efficient energy distribution. (Dahunsi et al. 2021, 71–72.)

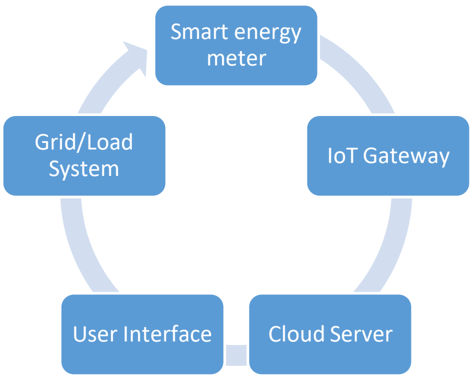


Figure 2: "The Continuous Feedback Loop of a Smart Energy Metering System (SEMS) in Biogas Plants"

The accuracy and efficiency play an important role in energy measurement, thus the selection of the right energy meter is crucial to ensure a smooth integration with the IoT platforms. The next section will provide an overview of the different energy consumption meters available in the market, evaluating their capacities and features in other to reach a verdict of choosing the right fit for the biogas plant.

3.1.1 Device Overview

Choosing the right energy consumption meters is critical for the overall operation of the VPP within the biogas plant. To a large extent, the selection of the appropriate fit dependence on the role that this device will serve within a specific biogas plant, in other words each project requirement affects the decision making regarding the selection of the device.

The market includes a variety of options to choose from according to each device preference. The following table represent some of these devices and their features which make them stand out in the market. This information is based on official product datasheets provided by the manufacturers and referenced accordingly.

Table 2: Comparison of Smart Energy Meters for Biogas Plant Integration

Device	Manufacturer	Company origin	Accuracy	Communication protocol	Power consumption	Integration with IoT	Availability in Finland
Schneider iEM3255	Schneider	France	Class 0.5S ±0.5%	Modbus RTU, Ethernet	Low	Cloud and SCADA Compatible	YES
Kamstrup OMNIPOWER	Kamstrup	Danmark	Class B (MID) ±1.5%	Wireless M-Bus, Modbus	Low	Cloud-based monitoring system	YES
Eastron SDM630-Modbus	Eastron	China	Class 1 ±1.0%	Modbus RTU (RS485)	Medium	Requires IoT Gateway	NO (can be ordered from other providers in Europe)

The selection of these specific devices for a comparative analysis is due to the quality these energy meters have to offer. According to the official product datasheets provided by the manufacturing companies, all selected meters meet with the MID (Measuring Instruments Directive 2014/32/EU), ensuring they comply with the EU standards for accuracy and performance while remaining within the budget. All the selected devices for the study are available in Finland, which makes it ideal for faster maintenance support, but other options have limited availability in Europe, requiring special orders and long delivery time. Additionally, many conventional meters lack smart communication features, making integration difficult or impossible. However, the features provided by the selected energy meters ensure effective integration with the biogas plant's VPP, allowing for remote monitoring and tracking as well as overall VPP optimization.

The next section will focus on comparing thesis different energy meters according to the criteria stated in table 1 to ensure the compliance with the overall view of the project and the guidelines given by the project manager. The following section will also include direct quotation from the interview to showcase further the view that the project manager has in regards of thesis energy meters, and the IoT solutions in general.

3.1.2 Comparative Analysis

The selection of the most suitable energy meter for the biogas plant VPP calls for a well structure comparative analysis of the key technical issue and the operational factors ensuring their alignment with the given criteria. The comparative study will evaluate the three energy meters Schneider iEM3255, Kamstrup OMNIPOWER, and Eastron SDM630-Modbus mentioned in table 2. The comparison will be based on the accuracy, ICT (information and communication technology) capability, power consumption, IoT integration, availability in Finland, and cost efficiency. The objective of this analysis is to determine the best device that aligns with the requirement in table 1, to ensure an overall enhancement of the biogas plant.

The first aspect this comparison will address is measurement accuracy. According to the official datasheets provided by each manufacturer, all three devices offer high measurement precision, though with slightly different levels of accuracy. When interviewed about the acceptable range of accuracy, Interviewee 1 (Project Manager) explained: “*It doesn't have to be like super high. So, for example, if it is plus minus a few percent, that is totally fine. Let's say if you find a device that has a, let's say, an accuracy of 1%, it is totally okay. If it has 2%, it is still fine*.” As shown in Table 2, all the proposed devices fall within the acceptable range defined by the interviewee, with accuracy levels between ±0.5% and ±1.5%. The interviewee also commented on the acceptable budget per energy meter: “*Let's say 1000 euro for one energy meter. That would be fine. But I know that, for example, if it is a few hundred, it is also fine. But maybe if it is over a thousand per meter, then it is too much.*” All the devices included in the study cost under 1000 euros which means that in terms of budget, these energy meters comply with the requirements perfectly.

Ranking first is the Schneider iEM3255 costing around €408.00 per unit according to Rexel, and providing the highest accuracy level among the three other devices at (±0.5%) thus it is the most suitable for extremely accurate measurement. Following closely is the Eastron SDM630-Modbus at the price of €219.00 per unit according to Rexel, and rated class1 and an accuracy percentage at (±1.0%) this level is still solid in providing dependable measurement making appropriate for commercial usage. Coming at the end is the Kamstrup OMNIPOWER listed at Bels.dk for €328.33 per Styk plus additional shipping cost as it can be challenging to get straight from a retailer in Finland. This meter is rated Class B (±1.5%). This percentage is the lowest among the devices, yet still provides sufficient precision for general domestic or commercial energy monitoring. (Table2.)

In conclusion, based on the accuracy percentage, the Schneider iEM3255 stands out as the most suitable device due to its ±0.5% precision and real-time data transmission making it stand out as the most suitable for the role in terms of accuracy and precise energy monitoring. However, Eastron SDM630-Modbus provides a good balance between accuracy and cost effectiveness.

While selecting the suitable device for the role it is crucial to take into consideration the communication protocol used by the device because this would determine the efficiency by which the device is going to transfer the data to the cloud platforms, SCADA systems, or IoT gateway. Considering that this device will be used in a biogas plant, easy integration, secure transmission, and flexibility is required. In this part, the focus will be on the communication and IoT integration aspect that each of these devices provides. The comparison will go through the protocol that each devices uses and how the IoT integration is set to be. The goal is to find which of the devices aligns the most with the given criteria.

According to the datasheet of each device, in terms of communication protocols Schneider iEM3255 offers Modbus RTU and ethernet based communication making it direct and ready to connect with cloud systems or SCADA infrastructure. In addition, Schneider iEM3255 offers seamless IoT integration without the need for any additional hardware using the plug and play compatibility with many other IoT platforms and third-party clod services. In the other hand Kamstrup OMNIPOWER uses a wirless M-Bus and Modbus communication protocols making suitable for places with minimal wired infrastructure and remote reading via supporting modular communication interfaces. Additionally, though wireless M-Bus might experience some transmission delays, it remains ideal for optional real time monitoring. Lastly, Eastron SDM630-Modbus depends on non IoT native Modbus RTU through RS485, which required the usage of an external protocol converter such as Modbus to MQTT/HTTP or IoT gateway to transfer the data to a cloud system. Thus, the integration process will be more complicated and less seamless compared to the other devices due to the additional integration effort. (Table 2.)

In summary, Both Schneider iEM3255 and Kamstrup OMNIPOWER offer enhanced Communication capabilities within an IoT based biogas plant monitoring with no set up integration needed as both uses plant and play approach with Schneider iEM3255 being perfect for wired and high-performance setups and Kamstrup OMNIPOWER good from remote locations as is release on wireless communication and Modular deployments. In the other hand Eastron SDM630-Modbus lacks the native IoT protocols requiring more effort throughout the integration presses making it the least favourable choice for the biogas VPP use case.

In another angle, the data collection and communication frequency factors are quite important for obtaining a seamless and efficient VPP workflow within a biogas plant. In smart grads it is often common to use a real time data collection and communication meters. However, it is wildly acceptable to use periodic meters that do the same job but within a reasonable time frame. When asked about the preferred data update frequency for an energy meter, *Interviewee 1 (Project Manager)* explained: "*It does not have to be real time, but it should not be every hour. That's not enough. So, for example, every minute is okay. Every five minute is probably fine. But maybe it should not be longer than five minutes because we need to do more or less some kind of regular update because the software that we are developing, that is the cases that we are developing are depending on the data that we collect. So therefore, it should not be maybe longer than five minutes.*".

Based on the datasheet of each device it can be challenging to find a clear mention on whether the meter enables real time monitoring or periodically. However, in Schneider iEM3255 datasheet it stated under Sampling rate that the device offers 32 samples per cycle which translate to 1600 samples per second at 59Hz or 1920 samples per second at 60Hz enabling a hight accuracy data collection as mentioned previously. Regarding the rate of the data collection and communication rate, this will depend on how frequently the Modbus master polls the device enabling a near real time data collection and transmission experience. In the other hand, Kamstrup OMNIPOWER though there is no clear setation of the frequency of the data communication, the datasheet is mentioned that the device is capable of a configurable load profile frame of 5, 15, 30 or 60 minutes which can be consider a periodic rate. Lastly, is Eastron SDM630-Modbus same as the other no clear mention of the information within the device datasheet. However, it is known from the same resource that the device relay on Modbus RTU communication therefore the device can either provide real-time or periodic monitoring depending on the polling interval configured in the master system. In conclusion, all the energy meters fit the profile when it comes to data collection and communication frequency, and it would be up to the project's decision makers to state which one fit the best in this regard.

3.2 Temperature Sensors

Temperature is a crucial indicator for an effective and efficient biogas plant workflow, as it can be related directly to amount of water in the raw biogas plant. In other words, the lower the temperature the lower amount of moisture. (Mandal, Kiran and Mandal, 1999. 3) Having an accurate measurement of the temperature has proven to be critical as it influence directly the biological activity that results to the production of methane. This production is a result of the anaerobic bacteria performance in the biogas plant which are considered highly sensitive to temperature changes as any small shifts can interrupt the production of the gas. The ideal temperature range for digesters operation is 30-40°C for mesophilic organisms and 50-60°C for thermophilic species. (Silva, Otto, Braggio and Kitamura, 2019. 1-2.). Therefore, the selection of the right temperature sensor is important for an overall seamless production. The following section will go through selected temperature sensors given an overview on these devices, then a comparative analysis will take place in order to identify the best option for the workflow. These sections will include the use of table 3 to visualize the comparison for more clarity.

3.2.1 Device Overview

As mentioned previously in section 4.4, the selection for the best fit temperature sensor in vital. Thus, the selection presses will go through the same given criteria in table 1, to ensure that the final decision in accurate and fit perfectly the need of the project. During the search of the suitable devices, it was clear that the market does not include up to standards stand-alone temperature sensors as most of which need other support systems for full integration and functionality. the search has been concluded by the selection of two temperature: E+E Elektronik EE310, and IFM TN2530. This identification has come as a result in the outstanding performance given by these devices in the market, such as the high accuracy, seamless integration, low power consumption, weather resilience, and availability within the EU.

Table 3: features overview of the temperature sensors

Devices	Manufacturer	Origin	Measuring range	Accuracy	Communication protocol	Integration with IoT	Availability in Finland
EE310	E+E ELEKTRONIK	Austria	-40 °C to +180 °C	±0.1 °C	Modbus RTU, Analog, Ethernet	Cloud, SCADA, IoT	YES, from the manufacturer with delivery worldwide
TN2531	IFM ELECTRONIC	Germany	-40 °C to +150 °C	±0.3 °C	IO-Link	PLC, SCADA, IoT plug-and-play	YES, direct from the manufacturer

Table 3 visualizes different aspects that the selected temperature sensors provide according to their datasheets offered by the manufacturer company. The key features used to compare the two devices are stated in table 1 based on the interview with the project manager. The usage of the table will be demonstrated throughout the next section to help provide a clear comparative analysis.

3.2.2 Comparative Analysis

This section will follow the comparison of two industrial grid temperature sensors E+E Elektronik EE310 and TN2531 focusing on their accuracy, communication protocols, integration, IP rating, and the availability of purchase in Finland. This analytic is based on information stated on the device's datasheets provided by the manufacturer and visualize in table 3.

First observation is that both devices demonstrate outstanding accuracy. The E+E Elektronik EE310 offers ±0.1 °C precision, making it ideal for precise temperature control, which is ideal for a more precise measuring, especially when a tight thermal control is in demand, thus within the sensitive environment of the biogas plant EE310 stand as a good fit for the role. In the other hand TN2531 performs an accuracy of ±0.3 °C making it well within the acceptable industrial range as the project manager stated in chapter 4.1. When it comes to temperature range that these sensors can perform under, we can notice some differences between the two, as EE310 supports measurements up to +180°C, while TN2531 reaches only +150°C, resulting to EE310 ranking higher in this regard than the TN2531.

In terms on communication protocol, EE310 present a wide range of protocols that the sensor supports such as Modbus RTU, Analog, and Ethernet. Thus, EE310 is compatible with multiple systems including cloud-based solutions. The TN2531 relay on IO-Link, which is a well-recognized point-to-point serial communication protocol allowing two-way communication with a plug and play configuration and a near real-time data transmission showing flexibility with IoT based environment. Both devices show strong features, however according to the project manager preference of the Modbus protocol, the EE310 gain advantage over TN2531. Nevertheless, TN2531 remains a strong choice for a seamless integration.

From the datasheet of the devices it is noticeable that both rated resilience against weather an harsh conditions within the workplace, the biogas plant in this case, as the E+E Elektronik EE310 is rated IP65 meaning it is solid proof against dust so no dust can enter the devise as well age been waterproof protecting the sensor against eater jets so if a cleaning with hose if it is to happen it would not cause any hard to the hardware. In the other hand TN2531 is rated IP67 making it dust resistant as well, however instead of just being protected against water its full proof against water submersion making it ideal heavy dusty, harsh and wet areas such a biogas gas plant. It is safe to say that both are good choices for the biogas plant environment.

Both devices are available to purchase in Finland through authorized resellers or directly from the manufacturer, showcasing the devices compliance with the EU standards. While the price is not listed in the official website of both sensors and require an official inquiry a search from other providers shows a range between €200 and €300 per unit posted in MT24 for TN2531, and range between €1000 and €1900 for the EE310 across different online providers. It is advisable to contact the manufacturer before the initialization on any purchasing operation to ensure cost efficiency and quality. In conclusion for a more cost-efficient choice, it is safe to say that TN2531 is well within the budget while EE310 can easily exceed the budges stated for the temperature sensor.

In conclusion, Both devices showed an astonishing performance across all the given criteria making then a good fit for the temperature monitoring within the biogas plat VPP framework. While EE310 showcase higher accuracy and wide range of communication protocols with an even wider temperature range, the TN2531 relay n a moder IO-Link as a communication protocol, more resilience toward the framework environment, and a more cost effective. The final selection will depend on the project needs such as the level of monitoring precision, integration flexibility and cost limitation. However, both sensors align perfectly with the criteria in table 1 and support integration with IoT solutions.

3.3 Wind Speed Sensors

One of the essential sensors for a seamless energy monitoring system in the biogas plant framework is the wind speed sensor, as it helps provide critical data such as the wind speed and direction. The data collected from these sensors is later used to improve the overall energy forecasting when integrated into a cloud-based VPP management system. It is important to note that wind sensors are considered a typical part of the smart energy grad framework within the EU-compliant energy infrastructure. (Zhang, Liu, Zhang, Yang and Wang, 2024. 1-2). The following sections will go through the different options available in the market for wind speed sensors, providing an overview on this hardware then comparing their criteria to help chose the right fit for the biogas plant.

3.3.1 Device Overview

To ensure that the overall VPP framework in the biogas plant works seamlessly, the selection of a reliable wind speed sensor was crucial. Thus, in this section an overview of the two industrial grad sensors will be discussed showcasing their criteria and how it aligns with the guidelines given by the project manager in table1. FT742-DM and VENTUS-UMB are two European manufactured wind sensors that are widely used within the region, the selection of these specific sensor came as a result in their good performance across the given criteria and their cost efficiency. Table 4 outlines the main criteria of the sensors, providing a visual and easy-to-follow summary based on their datasheets.

Table 4: An overview of FT742-DM and VENTUS-UMB wind speed sensor

Devices	Manufacturer	origin	Accuracy	Range	Communication Protocols	IoT integration	Availability
VENTUS-UMB	Lufft	Germany	±0.2 m/s	0–90 m/s	Binary, ASCII, NMEA, Modbus & analogue output	SCADA, Cloud, IoT Gateway	YES
FT742-DM	FT Technologies	United Kingdom	±0.3 m/s	0–75 m/s	RS485 or analogue 4-20mA output	IoT Gateway, Cloud and SCADA ready	Required contacting the manufacturer

3.3.2 Comparative Analysis

This section will contain an analytic comparison of the wind sensors; VENTUS-UMB and FT742-DM. The comparison will go through accuracy, communication protocols and data transmission, weather resilience, cost, and availability. The information used in the comparison is based on the technical datasheet provided by the manufacturer in their official website. Through out this section, table 4 will be used to help understand and spot the key criteria's differences, and similarities.

Accuracy, and as for the previous devices is a critical key feature that provide and idea of the quality of the data that the sensor will be collection, thus selecting the right wind sensor consist of considering their accuracy. It is undeniable that both wind sensors chosen for this comparison showcase an outstanding performance when it comes toto accuracy. However, standing at highest accuracy of ±0.2 m/s with a range up to 90 m/S VENTUS-UMB is considered to be suitable for precise monitoring and used in cases where precise monitoring is critical. Following closely is the FT742-DM. standing on ±0.3 m/s and a range up to 75 m/s this device still meets the standards requirement for general VPP monitoring, making it suitable choice for the biogas plant case.

To transfer the data collected, considering a sensor that can support a wide range of communication protocols is crucial for seamless monitoring. First, VENTUS-UMB supporting wide range of communication protocols such as RS485, SDI-12, Modbus, analog (0-10v and 4-20mA). This wide range result in a seamless integration into SCADA, PLC, and other IoT solutions. Compared to FT742-DM that support fewer window of protocols such as RS485 (SACII/NMEA) and analog 4-20mA output, yet this sensor is still meet the industrial standards options for integration. However, given the project manager preference for Modbus, VENTUS-UMB considered the most suitable fit in this regard.

The datasheet of both devices VENTUS-UMB, and FT742-DM highlights a clear environmental protection built into the hardware. VENTUS-UMB is rated IP68 showcasing a full protection against dust and water continues submerging making it suitable for undergoing hard environment conditions that can include the biogas plant surroundings. In the other hand FT742-DM is rated IP66(IP67 meaning that no dust can enter or damage the device regardless of the harshness of the surroundings, as well as a build in protection against water jets and temporary submersion, making it an industrial-standard option for the project. Though both provide strong resilience against environmental hazards such as water and dust, VENTUS-UMB has proved to be better option having additional certification for ice and marine use.

While the price of VENTUS-UMB is not directly listed on the manufacturer official website, the rough estimate based of retailer online such as eBay it is possible to make out a rough estimate of the price range going from €800 to €1500 depending on sensor configuration, and accessories. However, it is highly recommended to contact the manufacturer of origin for further information about the purchasing process before starting any deal with an official reseller. As for FT742-DM, coming at a lower cost of about €700 to €1000 it considered more cost efficient then VENTUS-UMB. However, this sensor can be challenging to purchase as there is to direct reseller that can provide, leaving the costumer to ace the only option of contact the manufacturer directly and negotiate purchasing the item and delivery to Finland.

In conclusion, based on the comparative analysis of both sensors it is noticeable that the hardware stands on a strong ground consist of solid accuracy and seamless integration with wide communication protocols and supporting system, and build in resilience toward dust and water submersion. However, the result of this compassion put VENTUS-UMB as the most suitable option for the biogas plant, as it is available to order through the manufacturer company or official online resellers. In another angle, FT742-DM also stands as a solid option that meet the EU standards and provide and easy integration with IoT workflow within the VPP framework. Yet, due to limited availability, considering this option it might be time consuming leading to a complicated process.

3.4 Sunlight Intensity Sensors

To enhance the overall energy efficiency and production with the vertical power plant framework in a hybrid biogas plant, it is crucial to use the solar intensity sensors. The changes that the solar irradiance experience throughout the day due to weather conditions and the change that occurred within different times in a day calls for a real time solar monitoring. A study carried out by Cao, Chen, Ren, Wang, Zhuang, and Zhou (2025), found out that the sunlight data was critical indicator for balancing and regulation the heat input in the biogas digester. It is important to note that without this sunlight data excess solar energy could go without being used efficiently. Therefore, having data gathered for solar measurement allowed for mor efficiency use and monitoring of energy and enhancing the overall output of the biogas plant within a VPP framework. (Cao *et al.*, 2025.)
The following section will go through different devices that enable solar measurement and monitoring and compare them to choose the right fit for better result in the biogas project carried by Centria.

3.4.1 Device Overview

Due to the crucial role that the solar intensity measurement plays in the biogas plant power efficiency, selecting the right sensor holds as much importance. Therefore, Hukseflux SR30 and Kipp & Zonen SMP10 the has been selected. Among the variety of industry grid sensors, these two devices stand out providing quality measurement thanks to hight accuracy and advances communication protocol and resilience against work environmental hazards. This section will include a table featuring all the criteria that these sensors have to offer facilitating the selection process of the most suitable fit for the plant. The table is based on the datasheet of each device provided by the manufacturer company.

TABLE 5: An overview of the key features of the sunlight intensity sensors.

Devices	Manufacturer	Origin	Accuracy	Communication protocols	Integration	Operation temperature	Availability in Finland
Hukseflux SR30	Hukseflux	Netherlands	Class A	Modbus RTU	Direct Modbus/ SCADA	-40°C to +80°C	Yes (Contact the manufacturer)
Kipp & Zonen SMP10	Kipp & Zonen (OTT HydroMet)	Netherlands	Class A	RS-485, Modbus, Analog 0-1V	SCADA/IoT ready with smart interface	-40°C to +80°C	Yes (Contact the manufacturer)

From table 5 it becomes evident that both devices showcase a hight industrial level performance. although, Hukseflux SR30 and Kipp & Zonen SMP10 have similar qualities across numerous criteria, both sensors showcase some differences in other. To find out the best fit for the biogas project, the flowing section will dive into the technical specification in table 4 more deeply outlining the strong and weak point of each hardware.

3.4.2 Comparative Analysis and Selection

Using information stated in table 5 and each device's datasheet the following section is constructed. Diving into different aspects to compare both sensors Hukseflux SR30 and Kipp & Zonen SMP10. This comparison analytics will go through accuracy, communication protocols and IoT integration, IP rating, finally cost and availability. This section will be closing with a conclusion of this comparison to propose the best fit for the plant.

When it comes to accuracy both devices hold a similar class certification as they are both classified ISO 9060:2018 Class A pyranometers, which places them in the top tier of solar irradiance providing precious and reliable measurements. Thus, Hukseflux SR30 and Kipp & Zonen SMP10 are both consider great choice for industrial level applications where high accuracy is required. Both sensors hold the ability to measure a full range of solar radiation relevant to energy production as Hukseflux SR30 hold a spectral range of 285-3000 nm while Kipp & Zonen SMP10 covers 310-2800 nm. These measuring ability with high accuracy put both devices at the same level of performance for the biogas plant's VPP where accurate measurements are crucial for the overall performance of the grade.

For a modern, digitally managed biogas plant, Modbus is a widely used communication protocol that is often used and widely used with SCADA system which is the case of the biogas plant project. Luckily, both sensors offer the same communication protocol. However, the SMP10 offers in addition to RS-485 and Analog 0-1v output. Making it eligible for seamless connection to both modern IoT platforms and analog monitoring system resulting to it being used in hybrid and legacy environments. Therefore, both devices offer a modern ways of communication protocols thus a seamless integration with the system. However, it is worth noting that for a wider range of compatibility SMP10 can be consider a better option in this regard.

Biogas plant can be considering a harsh environment for IoT devices, especially the outdoor once, as they get expose to all sord of different hazard that can harm the hardware such as water, dust, and temperature shifts especial in a Finnish environment where degrees often reach freezing degrees in winter. Choosing the right sensor must take into consideration all what has been previously mentioned. Therefore, the selected devices have an IP rating of 67 making them fully protected against dust and water explosion. These devices are also designed to be weather resistant providing a long operational life and reduces maintenance even if it has been installed in a rooftop with full exposure. As a result, both devices rank similarly in this aspect.

The information about the cost is cloudy as it is not really mentioned clearly for both sensors in their official websites, however Hukseflux SR30 and Kipp & Zonen SMP10 are considered premium devices, therefore, it is safe to assume the price can be quite high but at the same time it is hard to say for sure it will exceed the given budget. Both devices met the EU standards and are widely supported and available in Finland through the manufacturer's official website which offers help throughout the process with a customer service to resolve any issues that might happen. It is worth noting that the buyers must request quotes as a common procedure for industrial level grid hardware.

In conclusion, both devices showcase an outstanding industrial level performance across all criteria, although the price might not be officially stated by the manufacturers but given the outstanding aspects and features that these devices offer it is easy to assume a high price. However, as previously demonstrated these sensors had shown the reason behind the assumed high price from the high accuracy to modern communication protocols and high resilience. Making them durable and a great option for the smart grid.

4 DATA MANAGEMENT AND SECURITY

Data transmission in this thesis begins at the sensor level, where smart IoT-enabled devices capture real-time data such as power consumption, temperature, and wind speed. These sensors integrate seamlessly with automation systems by using industrial communication protocols such as Modbus RTU, IO-Link, and Analog outputs. Once gathered, the data is sent to an IoT gateway, either directly or through a converter that converts it to IoT-compatible protocols. The gateway processes and compresses raw data for cloud communication in forms such as MQTT or HTTP. This offers remote access and visualization via SCADA or cloud systems. Figure 3 depicts the whole transmission line from sensor to cloud. Plant operators can use centralized access to study and monitor data remotely, hence enhancing plant performance. Secure and reliable communication is critical for ensuring data accuracy, continuity, and protection throughout the process.

4.1 Data Transmission and Communication

The data collection this thesis began at the sensor level, as the industrial level IoT solutions proposed in chapter 4 were considered IoT enabled devices providing an automation reading and transmission of the data collected. This data can be electricity usage, temperature, wind speed, and sunlight intensity… These smart sensors relying on automation systems use industrial level protocols for communication such as Modbus RTU, IO-Link, and Analog output for seamless integration.
In this chapter will dive into the data transmission chain and communication after the raw measurements had been collected at the sensor level. To understand the process that the data foes through to arrive to the storage system (cloud/SCADA platform), figure 3 will serve as a visual demonstration of the process.

Figure 3: Sensor to Cloud Communication Process

As figure 3 illustrates, after the sensor collects the data, it is transmitted to the IoT gateway using communication protocols such as Modbus RTU, IO-Link, or Analog signals (table 2, table3, table4). These protocols ensure seamless integration with existing IoT solution or automation systems while maintains a smooth data transmission across different types of sensors. The data can be either send directly using Modbus or going first through converter or adapter that translate data into more IoT compactible format depending on the sensor design. (Wollschlaeger, Sauter and Jasperneite 2017, 4.)

The data now arrived to the IoT gateway; therefore, it needs to be sent to the cloud or SCADA platform. To enable this process the gateway process and package the raw data into format such as MQTT or HTTP, for a seamless communication with the cloud infrastructure, enabling remote access, visualization and further analysis of the data collected from all the sensors within the biogas plant in order to enhance the workflow process in figure 1. Once the data in stored in the cloud or SCADA platform it becomes accessible to authorizes users for analysis and filtering. This process leads to an easy remote monitoring and hybrid control upgrading the efficiency of the biogas plant. (Wollschlaeger *et al* 2017, 4-5.)

4.2 Data Storage and Access

VPP framework the data is collected from multiple distributed energy resources (DREs) such as biogas, wind and solar installations. This data is then stored on a centralizes cloud platform which offers scalability, rea-time data access and integration availability with visualisation dashboards and then the data driven decision making systems such as SCADA. Cloud storage enables remote monitoring of the energy production within the grid, forecast output, and an overall enhancement of the operation remotely. Within a VPP based bigos plant it is important to note that the data access must be fast, secure, and uninterrupted for better control over the plant and faster and more efficient emergency response. In some cases, it can be hard to rely totally on the could storage due to data corruption risk or some crushes of the could system which can affect data accessibility. Therefore, using edge computing or local storage is a good back up to keep the data available even if the internet connection is interrupted. Another solution can be by replying on the P2P systems, then the new era of integrating the Internet of Things (IoT) has touched various fields, enabled automation and optimized the operational processes. The data is shared between devices instead of been stored in one central data storage. With that said, the crucial point is to ensure that the access to this sensitive operational information is only through trusted authentication systems to people who are authorized, this can be done through secure login systems or encryption. (Ruan, Qiu, Sivaranjani, Awad & Strbac 2024, 2-6)

5 CONCLUSIONS

The thesis has gone through an examination of the market ready IoT solution that needs to be integrated within a biogas plant operating under virtual power plant (VPP) to improve the overall communication and remote monitoring for better outcome. A comparison analysis has been used in the study to compare these devices with a specific category such as energy meters, temperature sensors, wind speed sensors, and sunlight intensity sensors. The comparison was based on key criteria highlighted by the project manager including accuracy, communication protocol, manufacturer's origin, EU compliance, integration capability, and cost efficiency.

The comprehensive methodology used in this thesis involved literature review, manufacturers' datasheet, and an expert interview with the project manager. The analysis has been applied to different industrial grid IoT solutions such as OMNIPOWER, Siemens SITRANS, E+E EE310, and Ventus-UMB showcasing different choices available in the market for each category and featuring the key criteria of each device using tables for a better visualisation experience and easier understanding. All the devices used in the study are compliant with the EU standard and provide seamless integration with SCADA/IoT platforms or and IoT gateway to ensure all the requirements given has being met. Given the harsh environment that these devices will be performing under especially in the Finnish weather, a close look at the work environment and weather resilience of the most exposed sensors has been made ensuring a high performance under harsh conditions.

In addition, the thesis explores the importance of a proper data handling and management starting from the data transmission via communication protocols such as Modbus RTU and IO-Link to the data storage solutions using cloud based and on premises access. The study also highlights the importance for a local back up in case of internet shortage or data lose. The data security as well has been addressed as an important aspect using safety measures including encryption, authentication, and compliance to ensure safe and reliable data handing.

It is worth noting that after presenting the results obtains after the conduction of the study, the project manager expressed his satisfaction with the overall outcome as his opinion on the devices the has been suggested after each comparison aligned with his expectations. This comes as a result in following closely with the project manager and the thesis supervisor each step on the way and collecting feedback to make sure the result can be satisfactory and usable for the biogas plant project. This thesis server as a technical guid for the selection of the right IoT solution in each category enhancing the overall production process and enabling remote monitoring. The outcome will be used during the purchase of the devices to ensure that the biogas plant workflow efficiency, and smart within VPP ecosystem.

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APPENDIX 1

1. Accuracy and real time monitoring

What is the accuracy percentage that is acceptable by the project standards?

Is there a crucial need for real time data collection or can periodic be considered?

2. Connectivity and resistance

Does the choosing devices have to comply with existing IoT devices?

Is there any preference towards wired and wireless connectivity?

Is the weather resistance a crucial feature of the selected devices?

3. Data Handling & Communication

What is the communication protocol that should be followed?

4. Security threads

What are the potential security risks and security standards that should be considered?

5. Budget & Procurement

What is the given budget for the devices?

Should priority go towards cost or sustainability?

6. Power & Maintenance Considerations

What is the projected lifespan and maintenance frequency for the sensors and devices?

Who will oversee troubleshooting and maintenance following deployment?

7. Potential expansion

Is there any consideration for a potential expansion that the devices should support in the future?