



Energy monitoring system for industrial use

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Abstract:

Energy meters are essential for monitoring and managing electricity consumption across residential, commercial, and industrial environments. These devices enable consumers and utility providers to optimize energy efficiency, reduce costs, and support environmental sustainability, aligning with the EU's carbon neutrality goals for 2050. The advancement of smart meters has further transformed energy monitoring by providing real-time data collection, remote accessibility, and seamless integration with the Internet of Things (IoT). This thesis examines the differences users can expect when selecting an energy meter, focusing on metering methods and data logging capabilities. The study is conducted through a combination of literature review and mathematical calculations. The primary objective is to evaluate the performance and accuracy of a selected energy metering system by comparing it to a reference energy meter. The results indicate that a lesser-known measurement device can be a viable option for industrial applications, demonstrating promising measurement accuracy and user-friendly software that enhances the consumer experience. However, a key limitation of the study is the use of a Fluke a3001 FC current measurement device as a reference device, which has known accuracy limitations. Despite this, the findings suggest that the Shelly pro 3em energy meter offers reliable performance and ease of use, making it a competitive choice in the industrial sector.

Keywords:

Elcogen, Energy management, Energy Meter, Measurement Accuracy, Current measurement

Lärdomsprov

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Energy monitoring system for industrial use

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Sammandrag:

Energimätare är avgörande för att övervaka och hantera elförbrukning inom bostäder, kommersiella fastigheter och industriella miljöer. Dessa enheter gör det möjligt för både konsumenter och elleverantörer att optimera energieffektivitet, minska kostnader och bidra till hållbar utveckling i linje med EU:s mål om koldioxidneutralitet till 2050. Utvecklingen av smarta mätare har ytterligare förbättrat energimonitorering genom realtidsdatainsamling, fjärråtkomst och smidig integration med Internet of Things (IoT). Denna studie undersöker de skillnader som konsumenter kan förvänta sig vid val av energimätare, med fokus på olika mätmetoder och loggningsfunktioner. Studien genomförs för det mesta genom litteraturgranskning, med matematiska beräkningar som stöder undersökningen. Det primära målet är att utvärdera prestandan och noggrannheten hos ett utvalt energimätningssystem genom att jämföra det med en referensmätare. Resultaten visar att en mindre känd mätutrustning kan vara ett konkurrenskraftigt alternativ för industriella tillämpningar. Den uppvisar lovande mätnoggrannhet och ett användarvänligt program som förbättrar användarupplevelsen. En begränsning i studien är dock användningen av en Fluke a3001 FC-strömmätare som referensenhet, vilken har noggrannhetsbegränsningar. Trots detta tyder resultaten på att energimätaren Shelly Pro 3EM erbjuder pålitlig prestanda och enkel användning, vilket gör den till ett alternativ inom industrisektorn.

Nyckelord:

Elcogen, Energy management, Energy Meter, Measurement Accuracy, Current measurement

Table of Contents

Abstract:	2
Sammandrag:	3
Figures	6
Tables	6
Equations	6
List of abbreviations	7
1 Introduction	8
1.1 Elcogen as a company	9
1.2 Objective, purpose and research methods	10
2 Technical comparisons	13
2.1 Handheld measuring devices	15
2.2 Permanently installed measuring devices	16
2.2.1 Current transformer measurement device	16
2.2.2 Direct connected measurement device.....	18
2.3 IoT devices.....	19
3 Product comparison	20
3.1 Shelly Pro 3EM.....	20
3.2 Carlo Gavazzi EM330	20
3.3 ABB B24 energy meter	21
3.4 ABB D13 energy meter	21
4 Cloud software comparison	22
4.1 Shelly cloud	22
4.2 Carlo Gavazzi EM ²	23
4.3 ABB InSite system.....	24
4.4 Price comparison	25
4.5 In conclusion.....	27
5 Installation and testing	28
5.1 First test.....	29
5.2 Second test	32
6 Summary	37
6.1 Further development work	38
7 Sammanfattning	39

References 44

Figures

Figure 1. photo on the left is the cell, photo in the middle is the stack and the photo on the right is the module. (Elcogen, 2024)	10
Figure 2. Inside of a wound current transformer (Roderick, 2021).....	17
Figure 3. Inside of a window type current transformer (Roderick, 2021).....	17
Figure 4. a bar type current transformer (Roderick, 2021).....	18
Figure 5. Showcase of the Shelly software (Shelly 2, 2025).....	23
Figure 6. Screenshot of the EM2 software (Carlo Gavazzi, 2025).....	24
Figure 7. Screenshot of the Abb software (ABB 3, 2025)	25
Figure 8. Left, a photo of a wiring scheme on the Shelly device. Right, a photo of how the Current transformers were installed.....	29
Figure 9. total average power usage	30
Figure 10. Screenshot of the Shelly Cloud application showing energy measurements of one conditioning cycle.....	30
Figure 11. Screenshot of the data extracted from the Shelly device	33
Figure 12. Current measurement difference Phase A.....	34
Figure 13. Current measurement difference Phase B	35
Figure 14. Current measurement difference Phase C	35

Tables

Table 1. Price comparison (Onninen, 2025).....	26
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Equations

Equation 1.....	14
Equation 2.....	14
Equation 3.....	14
Equation 4.....	18
Equation 5.....	18

List of abbreviations

IoT – Internet of Things

CT – Current Transformer

EM – Energy Meter

Wh – Watt-hour

LED – Light Emitting Diode

IP – Internet Protocol

A – Ampere (unit of current)

UTC – Coordinated Universal Time

AI – Artificial Intelligence

CSV – Comma Separated Values (referencing data formats)

1 Introduction

The EU climate policy builds up on previously agreed policies such as the United Nations Framework Convention on Climate Change, the Kyoto Protocol to the Convention and Paris Agreement on Climate Change. Short term goals of this policy are to reduce greenhouse gas emissions by 55% by 2030, compared to the greenhouse gas emissions in 1990. In the bigger picture, the EU wants to achieve carbon neutrality by 2050, meaning that emissions and waste are balanced out according to the regulations by EU legislation. The EU emissions Trading system (EU ETS) is a guide to help EU to achieve the carbon neutrality target for 2035. (Ympäristöministeriö, 2024)

Another goal of the EU Emissions Trading System is the introduction of a new emissions trading system (ETS II) for fuel distribution, scheduled to take effect between 2027 and 2028. It will cover CO₂ emissions from road transport, building heating, most off-road machinery, and certain energy and industrial plants not included in the main emissions trading system. ETS II will also include a Social Climate Fund to support a fair transition to cleaner energy. The fund will help vulnerable groups by improving energy efficiency in buildings, supporting cleaner heating and cooling systems, and making low-emission transport more accessible. (Ympäristöministeriö, 2024)

The major goal for Finland is to reduce emissions from the effort sharing sectors, that contains transport, agriculture, building heating and waste by 50% when comparing 2030 levels with the levels of 2005. Finland has also set a goal for carbon neutrality for 2035, exceeding the goal of 2050 that was set by EU. (Ympäristöministeriö, 2024)

Elcogen adheres to the ISO 14001 standard, the standard is known as the standard of environmental management system (ISO, 2015). The standard correlates with Finland's goals to reduce emissions from the effort sharing sectors. By adhering to this standard, Elcogen aims to monitor high energy consuming units and optimize energy usage in the future. The objective of this thesis is to design, implement, and test an energy monitoring system capable of continuously measuring energy consumption. This will enable more accurate sustainability reporting, including life cycle assessment (LCA) reports, and help

with future optimizations for the conditioning units as well as the material testing furnaces.

Stack conditioning is a crucial part of the production process, ensuring optimal performance for the stacks. During this process, stacks are placed inside a conditioning unit for approximately 24 hours, where the stacks are heated up to 700 degrees where all organic material is burned away, and the glass gaskets melt making a seal that prevents any leakages. The stack is then tested to verify proper functionality both during and after conditioning. Solid oxide technology requires high temperatures to function correctly. To maintain the necessary heat, the conditioning unit is equipped with heating elements that activate or deactivate based on internal temperature readings using temperature sensors.

Material testing furnaces are used for long-term tests to evaluate the degradation of coating materials that are used on the stacks. These furnaces operate using the same temperature regulation technology, with heating elements cycling on and off to maintain the desired temperature. Since these tests can last anywhere from hundreds to thousands of hours, energy consumption is relatively high.

1.1 Elcogen as a company

Elcogen, founded in 2001, is a European clean energy technology company specializing in solid oxide technology. The company's SOFC and SOEC technologies are recognized for their high efficiency, flexibility and reversibility. Operating at temperatures as low as 650 °C, Elcogen's stacks achieve electrical efficiencies above 75% in fuel cell operation and hydrogen production requiring 33 kWh to produce one kg of hydrogen. This efficiency is achieved through their planar anode-supported cells, innovative stack design, and low operating temperature of 570-720 °C. (Elcogen, 2024)

Elcogen's products are designed for integration into various applications, including residential, commercial, and industrial power generation units, as well as green hydrogen production. However, these products cannot be directly integrated into the above-

mentioned systems. Instead, they require the creation of a stack before deployment. The company offers three main product families: (Elcogen, 2024)

- **Solid Oxide Cells:** Planar, ceramic and anode supported cells operating at 600-800°C, see Figure 1. left.
- **Solid Oxide Stacks:** Stacks using solid oxide cells and low-cost materials designed for mass manufacturing, see Figure 1. middle.
- **Stack Modules:** are used to integrate one more stacks into one system, see Figure 1. right.

Headquarters in Tallinn, Estonia and subsidiary in Vantaa, Finland, Elcogen serves a global customer base. The company has supplied its technology to over 160 customers across 30 countries. Overall, Elcogen is a leader in advancing solid oxide technology and hydrogen production, contributing significantly to the global transition toward sustainable and emission free energy solutions. (Elcogen, 2024)



Figure 1. photo on the left is the cell, photo in the middle is the stack and the photo on the right is the module. (Elcogen, 2024)

1.2 Objective, purpose and research methods

The ISO 14001 standards, which Elcogen adheres to, are known as the standard for environmental management systems. Following this standard means Elcogen must continuously improve and adopt strategies to minimize their environmental footprint. ISO 14001 provides a framework on how to implement an environmental management system while

the goals set under ISO 14001 for Elcogen are not imposed by external organizations but are instead defined and implemented by its own management. This self-driven approach places a strong responsibility on the organization to follow through on its energy management strategies. (ISO, 2015)

A notable environmental impact for any company is high energy consumption, that is why implementing an energy monitoring system for high energy consuming units is important, such as conditioning units, that condition the stacks making them ready for commercial use, and material testing furnaces that test materials at high temperature for degradation over time. While the conditioning units are designed for continuous operation, starting with new stacks as soon as the previous ones are ready, the material testing furnaces can run for thousands of hours at a time, both consuming significant energy in the process. Ideally, all equipment operates continuously. An energy monitoring system is useful for monitoring the energy consumption of the conditioning units and material testing furnaces. This data is used to implement energy management systems for future projects and systems that require them for the LCA reports and sustainability reports aligning with the ISO14001 standard that Elcogen has implemented. Identifying and being able to monitor when and where energy consumption increases is a big step towards a more energy efficient industry. (Elcogen, 2024)

Energy meters are useful in industrial settings as they help monitor energy use in real time, improve efficiency, and reduce costs. Over the years, traditional electromechanical meters have been gradually replaced by electronic and smart meters, which provide more accurate readings and easier access to data. (Electric, 2025) The introduction of IoT and cloud-based systems has further advanced energy monitoring, enabling industries to track consumption more effectively. (ThingsBoard, 2025) Current research is exploring the use of AI and wireless metering technologies to enhance energy efficiency. (ThingsBoard, 2025)

The aim of this thesis is to analyze and compare various energy measurement systems for industrial applications. Additionally, the energy requirements will be assessed using technical data sheets of the machines that require monitoring, determining their maximum power consumption. By evaluating different installation methods, measurement accuracies, IoT solutions, software options, and cost factors, this thesis will identify the most suitable energy management system for Elcogen.

2 Technical comparisons

To measure energy consumption, it's important to consider devices that offer continuous real-time monitoring. Various types of energy meters are available, each with different features that may be suitable for specific environments. Choosing the right device depends on the specific needs and requirements. (Chint Global, 2022)

When selecting an energy meter, the key factors to consider are reliability and measurement accuracy. Additionally, a measuring device that is simple and efficient for data collecting is prioritized. The energy meters need to be able to measure currents up to 125 A, because of the high current consumption of the conditioning units and voltages in a 3-phase configuration. For these reasons, various options for an energy measurement system have been explored. measurement accuracies for static watt-hour meters are 0.5 (C), 1 (B) and 2 (A). These measurement accuracies indicate the percentage of measurement inaccuracies that occur when measuring current, for example in heavy industries where energy measurements need to be precise is an accuracy class C energy meter required, but in light industries an energy meter with an accuracy class B is sufficient. (Eastron, 2024). The Directive 2014/32/EU states that measurement of light industrial use is allowed by any class B meter. (EUR-Lex, 2014). Light industries are defined as industries that consume less energy than cement or steel manufacturers (Iea, 2023).

Elcogen falls under the category of light industries, allowing Elcogen to use class B energy meters. That is why every measurement system reviewed in this thesis has an accuracy rating of B. This indicates that the current transformers have a current measurement accuracy of $\pm 1\%$, and in the rare case that the voltage measurement is available like in the Shelly pro 3em, the voltage measurement accuracy is also $\pm 1\%$. (Shellykauppa, 2024)

When calculating power for a device in a 3-phase configuration with a current measurement accuracy of 1% , can you simply use the power equation. (Vertiv, 2025)

$U = \text{Voltage}$

$I = \text{Current}$

$\cos\phi = \text{power factor}$

$\pm 1 \% = \text{measurement accuracy for the device}$

$$\Delta P = \sqrt{3} \cdot U \cdot (I \pm (1 \% \cdot I))$$

Equation 1.

ΔP (Wh) is the actual power that is measured or calculated, while U is the voltage, and I is the current the device measured is using. The power factor ($\cos \phi$) is the variable that describes how effectively the device uses electrical power in AC systems. But when more than one inaccurate variable emerges when calculating measurement accuracy, you must use the uncertainty in a function of several variables. (Taylor, 1996)

$$\Delta U = 1 \% \cdot U$$

$$\Delta I = 1 \% \cdot I$$

$$\Delta P = \sqrt{(\sqrt{3} \cdot I \cdot \cos \phi \cdot \Delta U)^2 + (\sqrt{3} \cdot U \cdot \cos \phi \cdot \Delta I)^2}$$

Equation 2.

Which when simplified is

$$\frac{\Delta P}{P} = \sqrt{\left(\frac{\Delta U}{U}\right)^2 + \left(\frac{\Delta I}{I}\right)^2}$$

Equation 3.

$$\frac{\Delta P}{P} = \sqrt{(0.01)^2 + (0.01)^2} = 0.0141 = 1.41 \%$$

Here, $\frac{\Delta U}{U}$ and $\frac{\Delta I}{I}$ represent the relative uncertainties in the voltage and current measurements. Since the power factor $\cos \phi$ is an assumed constant, that does not contribute to the uncertainty, simplifying the calculation to only consider the uncertainties of voltage and current. $\cos \phi$ is an assumed constant because it is the power factor for the machines inside the conditioning unit that don't change during operation. But when

wanting to calculate the actual power we need to include them in the equation as shown in Equation 2. (Taylor, 1996)

This result indicates that, without considering other factors, the uncertainty in the power measurement would be 1.41 %. However, energy measurement devices like the Shelly pro 3em achieve a 1 % measurement accuracy by employing calibration techniques and error-correction algorithms that compensate for the initial uncertainties in voltage and current measurements. These methods ensure that the final power measurement stays within the required accuracy range of 1 %. (Shelly 1, 2025)

2.1 Handheld measuring devices

Handheld measuring devices are designed for use over a specific period, making them unsuitable for long-term measurements that require continuous energy monitoring. Additionally, these devices are typically powered by batteries, which further limits their ability to support extended energy monitoring. (Fluke, 2025)

While doing testing, the Fluke a3001 fc current clamp meter will be used as a reference for current measurement accuracy. The reason for this is that Fluke is a well-known measurement device supplier that has a long history in these devices. Elcogen has also used the Fluke a3001 fc for previous current measurements. The Fluke a3001 fc has a current measurement accuracy of ± 3 % because of its high current range, the current range for the Fluke a3001 is 1-2500 A. (Fluke, 2025)

2.2 Permanently installed measuring devices

DIN rail-installed measuring devices, as the name suggests, are designed to be mounted onto DIN rails commonly found inside electrical cabinets. These devices remain connected to the circuit, drawing power directly from the electrical grid, enabling them to measure electricity consumption continuously as long as the system is powered. When selecting a DIN rail measurement device, it is important to consider the type of system you wish to install. Specifically, you need to decide whether a current transformer energy meter or if a direct-connected measurement device is more suitable for your requirements. (Polycase, 2020)

2.2.1 Current transformer measurement device

A current transformer is a measuring instrument designed to step down high primary currents to lower, secondary currents, enabling the energy meter to be able to measure high current loads. The secondary current typically has a standard rating of 5 A, with a fixed primary to secondary ratio (ElectronicsTutorials, 2025). There are 3 different types of current transformers: (Roderick, 2021)

Wound current transformer: Wound current transformers have a separate primary and secondary winding that are wrapped around a laminated iron core. A wound current transformer works by having its primary winding made up of one or more turns of thick wires. The primary winding induces a proportional current in the secondary winding, maintaining a specific ratio. These wires are connected directly in line with the electrical circuit you want to measure. This setup allows the transformer to monitor the current flowing through the circuit (see Figure 2.). (Roderick, 2021)

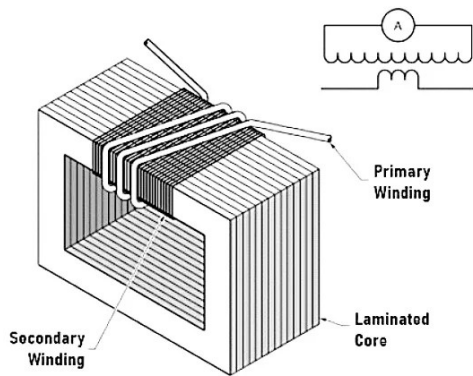


Figure 2. Inside of a wound current transformer (Roderick, 2021)

Window-type current transformer: Window current transformer consists of a secondary winding wrapped around a core, and the primary sent through the window. The core is then insulated with 2 taps coming out that sends a lower secondary current to the measurement device (see Figure 3.). (Roderick, 2021)

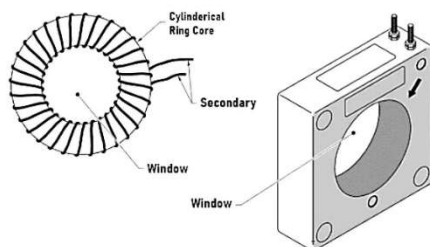


Figure 3. Inside of a window type current transformer (Roderick, 2021)

Bar-type current transformer: A busbar current transformer is a type of window transformer that has a solid bar running through it (see Figure 4.). It is designed to handle high over currents without getting damaged. However, to prevent magnetic forces from damaging the transformer or the busbar, it's important to mount it correctly and keep it properly aligned with nearby conductors. (Roderick, 2021)

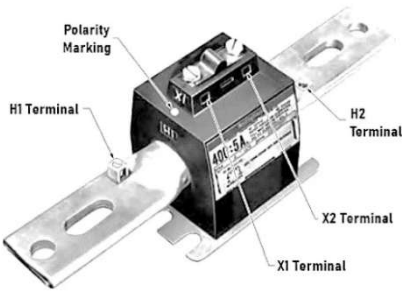


Figure 4. a bar type current transformer (Roderick, 2021)

Like any other transformer, the current transformer must follow the amp-turn equation.

$$n = \frac{N_p}{N_s} = \frac{I_s}{I_p}$$

Equation 4.

Which can be transformed into.

$$I_s = I_p \left(\frac{N_p}{N_s} \right)$$

Equation 5.

This means that the secondary current (I_s) can be calculated by multiplying the primary conductor's (I_p) current by the ratio of the windings in the primary (N_p) to the windings in the secondary circuit (N_s). (ElectronicsTutorials, 2025)

2.2.2 Direct connected measurement device

Direct connected measurement devices offer another method of energy measurement. While they provide greater accuracy and precision than current transformer measurement devices, they are not without their limitations. Direct-connected devices are often shunt-based energy meters. The shunt-based energy meter is more precise than the current

transformer devices, however this design limits the maximum current capacity they can measure, any current rating over 100 A often requires a current transformer. Despite this limitation, they excel in providing highly accurate power usage measurements. That is why electrical billing companies, like Vantaan Energia usually use direct connected measurement devices for commercial buildings that don't exceed the current ratings for a direct connected measurement device. (Sercu, 2024)

2.3 IoT devices

Internet of Things (IoT) devices are systems that communicate with other IoT devices or have the ability to send data automatically to dedicated databases, transforming traditionally "dumb" devices into interconnected, intelligent tools through internet connection. This enables commonly used devices, such as lamps, locks, and sensors, to detect movement and communicate with each other to enable a function. For example, an energy measurement device that can communicate with a database, like the Shelly cloud automatically, can send data and inform the consumer of any irregularities that are happening during the power consumption cycle, making it easy to notice any problems. (Gillis, 2023)

In this case, a sensor capable of communicating with a database in a server and automatically sending data to the database would be ideal for Elcogen's needs. This setup allows energy consumption to be monitored from anywhere with internet access, making it more convenient to use and collect the data generated by the energy meter.

3 Product comparison

The product comparison will cover three different current transformer devices and one direct connected device. In addition, software and price are compared later in the degree thesis.

3.1 Shelly Pro 3EM

The Shelly Pro 3EM is an energy meter that measures power using current transformers and has an accuracy class of B ($\pm 1\%$). This energy meter leverages IoT technology, providing access to its dedicated database storage. The database stores data and generates easy to read graphs, offering a clear visualization of the energy usage of the device being measured. (Shelly 1, 2025)

The Shelly device can measure data at intervals as short as one minute. However, while measurements are taken every minute, the software displays the data as an hourly average. For more detailed data, users can download it directly through the device's designated IP address. (Shelly 2, 2025)

The Shelly system is a compact, precise, and cost-effective solution for measuring power consumption using current transformers. The only drawback that can be mentioned is the absence of an LCD screen on the unit itself. (Shelly 1, 2025)

3.2 Carlo Gavazzi EM330

The Carlo Gavazzi EM330 uses the same technology for energy measurement as the previous device. The EM330 employs Modbus technology for data transfer, therefore a data logger is required for IoT-based data collection, the data logger can then transmit the data via Wi-Fi or Ethernet to a cloud-based program provided by the manufacturer. (Onninen, 2025)

The EM330 has an accuracy rating of B ($\pm 1\%$) and features an integrated LCD screen, allowing local data monitoring. The only drawbacks of the EM330 are that it requires data collection to be able to collect data automatically to a database. This means the system needs additional space for installation, which could pose challenges in areas with limited space. The energy meter does not include current transformers in the packaging, meaning that they must be bought separately. (Onninen, 2025)

3.3 ABB B24 energy meter

The ABB B24 energy meter uses the same current transformer technology to measure energy consumption as the other previously mentioned devices. Like the EM330, the B24 uses Modbus technology for data transfer, meaning a data logger is required to transmit data to a database. (ABB 1, 2025)

The B24 has an accuracy rating of B ($\pm 1\%$) and features an LCD screen for local monitoring of power consumption. The B24 suffers the same drawbacks as the EM330, the need for a data logger, the cost, space needed for the installation and the lack of current transformers. (ABB 1, 2025)

3.4 ABB D13 energy meter

The D13 energy meter utilizes direct connection technology to measure energy consumption. Like the EM330 and the B24, the D13 uses Modbus technology for data transfer, meaning a data logger is required to transmit data to a database. (ABB 2, 2025)

The D13 has an accuracy rating of B ($\pm 1\%$) and features an LCD screen for manual data collection. The biggest drawbacks of the D13 are its limitation to recording data for current ratings over 65 A, as well as the previously mentioned requirement for a data logger to enable cloud-based data collection. (ABB 2, 2025)

4 Cloud software comparison

When comparing software options, it is important to prioritize features that align with Elcogen's needs. User-friendly software with an intuitive interface and customization options is preferred. Most importantly, the software must ensure a stable and reliable connection with the device.

4.1 Shelly cloud

The Shelly Cloud application is an IoT device manager that is used for managing, monitoring, and automating all Shelly devices within a single app. Real-time energy consumption, as well as total energy consumption over a specific period, can be tracked. With a premium subscription, monthly energy consumption reports can also be received (see Figure 5.).

The Shelly Cloud app is compatible with mobile devices and can be seamlessly downloaded for free from the App Store and Google Play Store.

A simple and user-friendly way is provided by the app for connecting devices to a Shelly account, making the activation process straightforward. Shelly devices can be connected to the internet using Bluetooth, AP scan, or network scanning when an Ethernet cable is used.



Figure 5. Showcase of the Shelly software (Shelly 2, 2025)

The premium subscription, which costs 36€ per year, includes additional features such as monthly energy usage reports, notifications when a Shelly device goes offline, and alerts for abnormal energy usage. These alerts are powered by AI, providing insights tailored to the system's typical behavior. (Shelly 2, 2025)

4.2 Carlo Gavazzi EM ²

EM2 is a professional energy management software capable of managing data from up to 100 energy meters simultaneously. Users can view and manage both past and real-time data through a web interface accessible via popular browsers such as Google Chrome, Firefox, or Safari. Figure 6. shows a graph for 1 day's energy usage. (Carlo Gavazzi, 2025)

Like the Shelly Cloud platform, the EM2 software can analyze energy usage, identify trends, and create a virtual energy meter that consolidates all collected data, making energy monitoring as simple and efficient as possible. (Carlo Gavazzi, 2025)

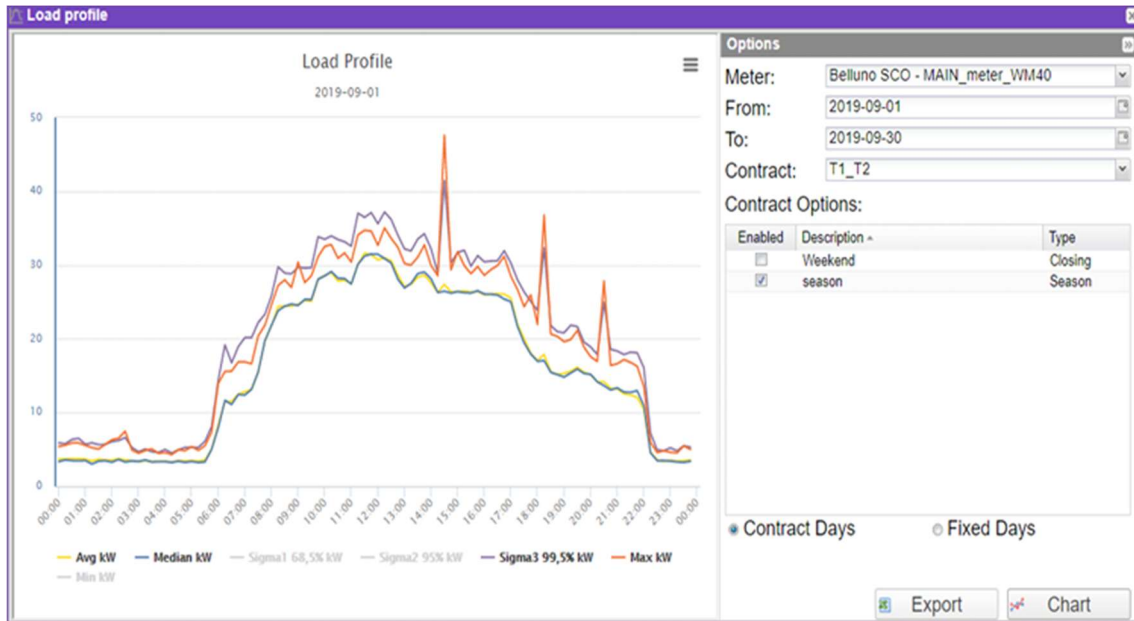


Figure 6. Screenshot of the EM2 software (Carlo Gavazzi, 2025)

EM2 operates on a virtual machine running Linux as its operating system. This virtual machine includes everything necessary for data management and control, a database, an operating system, and a web server. The EM2 can store detailed data for up to 10 years and less detailed data for up to 30 years. Additionally, backup tools are provided to ensure data retrieval is possible if needed. The software starts with a license for 20 energy systems, with the option to expand if needed. The system supports a maximum of 100 energy systems. (Carlo Gavazzi, 2025)

4.3 ABB InSite system

Like the EM2, the ABB InSite energy monitoring software is a web-based software making it easy to use. It is exclusively designed for energy monitoring and management, making it a good and reliable energy monitoring tool for industrial use (see figure 7.). The InSite software offers similar features to the EM2, making them quite alike. (ABB 3, 2025)

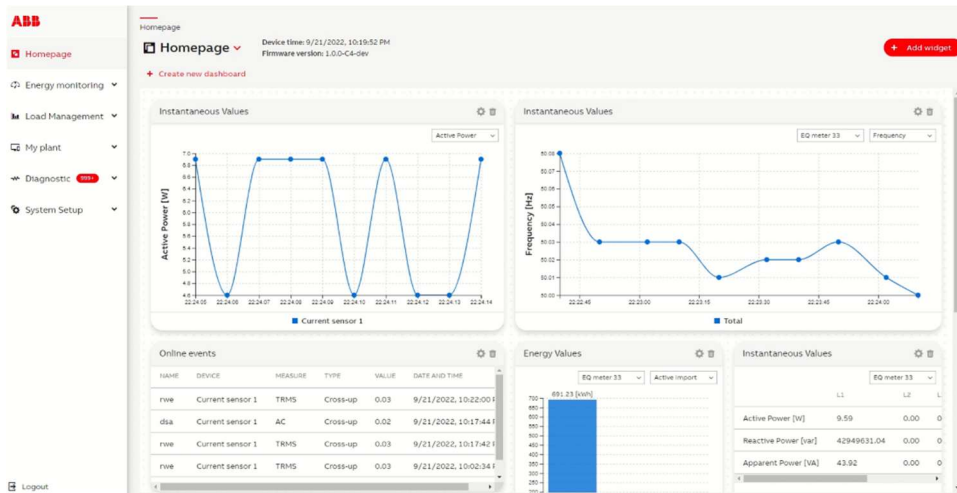


Figure 7. Screenshot of the Abb software (ABB 3, 2025)

The ABB InSite energy management system provides the same real-time monitoring capabilities as the EM2 and Shelly Cloud, ensuring accurate and effortless energy tracking. This feature is essential for simplifying energy monitoring and improving precision. Additionally, the InSite system includes alerts and notifications for abnormalities, such as sudden current drops during device testing, similar to the EM2 and the premium subscription features of the Shelly Cloud. The software supports widely used Modbus and OPC connections, offering flexibility for organizations seeking seamless integration with existing devices. (ABB 3, 2025)

4.4 Price comparison

For a fair price comparison, all the prices listed in Table 1. have been sourced from Onninen's website. These are shelf prices, meaning that if a customer requested a quote, the actual price would likely be lower. As a result, the listed prices may not reflect the final price a company would receive. However, this method remains valid for price comparative purposes.

Table 1. Price comparison (Onninen, 2025)

Energy meters	Shelly pro 3em	Carlo Gavazzi EM330	ABB B24 Energy meter	ABB D13 Energy meter
Price of energy ammeter >125 A	273 € + 1 extra current transformer 37.20 €	224 € + 144 € x 4 Current transformers	354 € + 40 € x 4 Current transformers	No meters available to measure 125 A or up
Price of an energy meter <125 A	137 € + 1 extra current transformer 16.90 €	224 € + 98.50 € x 4 Current transformers	354 € + 40 € x 4 Current transformers	215.00 €
Price of the Datalogger	Datalogger included	953 € + Power supply 83.60 €	869 € + Power supply 83.60 €	869 € + Power supply 83.60 €
Total price for one >125 A system	310.20€	800.00 €	514.00 €	Not possible with this meter
Total price for one <125 A system	159.90€	618.00 €	514.00 €	215.00 €
1 datalogger per measurement system	Internal datalogger	1,036.60 €	952.60 €	952.60 €
Total price for an energy meter system for the conditioning units + compressors	6 measurement devices 923.40 €	6 measurement devices + datalogger 4916.6 €	6 measurement devices + datalogger 34036.6 €	Not possible to measure all devices

4.5 In conclusion

The software mentioned above shares similar capabilities and features, with reliable energy monitoring as their standout feature. However, there are subtle differences in appearance and user simplicity. Both the ABB InSite and EM2 energy monitoring software are well-established brands, renowned for their reliability in industrial applications. Meanwhile, Shelly Cloud stands out as a strong contender, offering user-friendliness with its straightforward design.

Additionally, all three systems allow users to extract precise data into Excel sheets, making it easier to monitor and analyze the performance of the measured units more effectively and reliably.

When comparing prices from Table 1., it is clear that the Shelly product is significantly more affordable than the other well-known brands. In the worst-case scenario, the Shelly system is four times cheaper than its competitors. This means that an entire Shelly system for five different devices can be purchased for less than the cost of a single energy meter and data logger from a well-known brand.

5 Installation and testing

The installation was carried out by a certified electrician. As a safety measure, the main power switch was temporarily switched off before the installation process began. The device was mounted in the electrical panel, following standard installation procedures.

The L1, L2, and L3 phase conductors, along with the neutral (N), were connected to their respective terminals (see Figure 8 Left). The current transformers (CTs) were correctly positioned around each phase conductor, ensuring proper orientation (see Figure 8 Right). The CT that was purchased separately to monitor the neutral conductor was found to be incompatible, as the Shelly Pro 3EM uses two-pin connectors for CTs, while the purchased CT had a four-pin connector. As a result, the neutral conductor could not be monitored until a new CT is received and installed. After the wiring was completed, the device was connected to the Wi-Fi network for remote monitoring.

Once the installation was completed, the power supply was turned on again. The LED lights on the device were checked to verify that it had power, and the Shelly Smart Control App was then used to confirm that voltage, current, and power readings were being registered correctly. Since the device was factory-calibrated, no further accuracy adjustments were required.

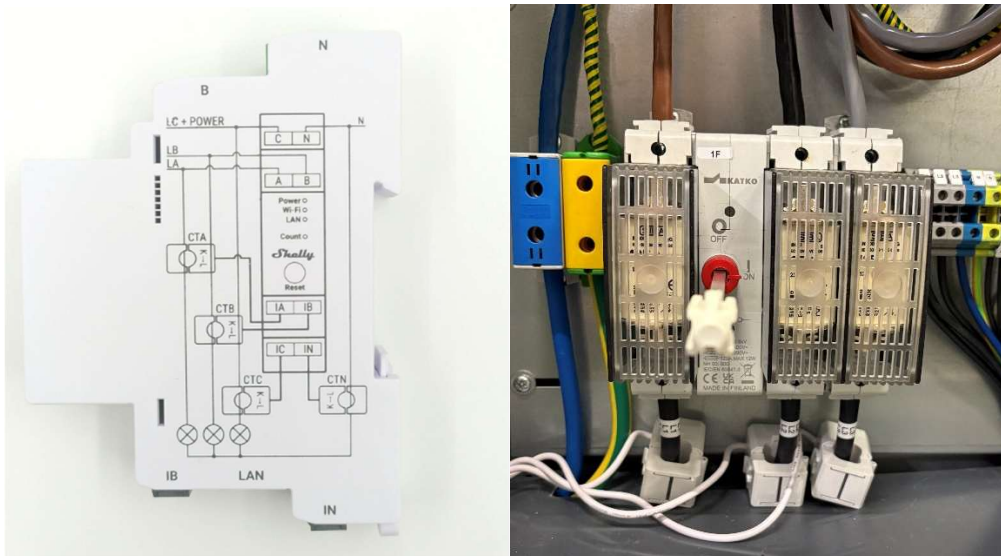


Figure 8. Left, a photo of a wiring scheme on the Shelly device. Right, a photo of how the Current transformers were installed.

5.1 First test

The first test for the Shelly device was conducted shortly after installation. The objective of the test was to verify that the device functioned properly during one full conditioning cycle. The test was performed under normal stack conditioning conditions, meaning that stacks were installed and conditioned simultaneously.

The conditioning process was carried out without any issues. The recorded data was easy to read, with no loss of information shown during the logging process. Figure 10. shows the data graph available on the Shelly Cloud application, where a realistic representation of the conditioning unit's energy consumption is displayed. The fluctuations in power consumption can be observed in Figure 9. these are caused by the activation and deactivation of the heating elements inside the conditioning unit. This occurred because the unit was designed to maintain a specific temperature, with thermal sensors used to regulate the current flow. These sensors were responsible for activating or deactivating the resistors as needed to ensure a stable internal temperature.

As shown in Figure 9., the data was displayed in one-hour intervals, meaning that the values presented were averages of the one-minute measurements recorded by the Shelly Pro 3EM, in accordance with the manufacturer’s specifications.

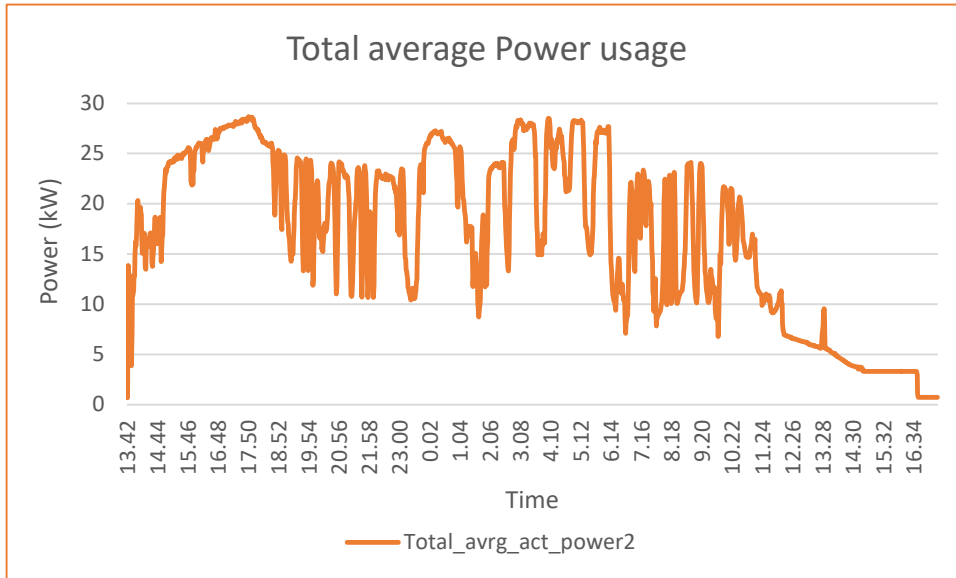


Figure 9. total average power usage

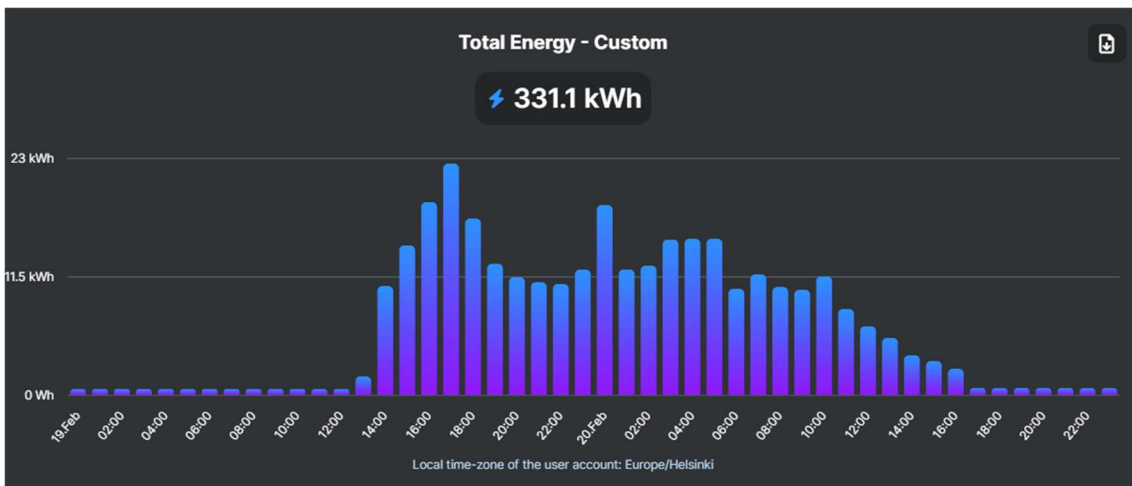


Figure 10. Screenshot of the Shelly Cloud application showing energy measurements of one conditioning cycle

As previously mentioned, the Shelly Pro 3EM has an accuracy rating of 1 %. This indicates that the total energy consumption for a conditioning cycle is not exactly 331 kWh, as shown in Figure 10. To assess this, we can apply the 1 % measurement accuracy

claimed by Shelly after calibration and compare it with the accuracy calculated in Equation 3.

$$331 \text{ kWh} \cdot 1 \% = \pm 3.31 \text{ kWh}$$
$$331 \text{ kWh} \cdot 1.41 \% = \pm 4.66 \text{ kWh}$$

This implies that the maximum difference between the two calculations is 2.3 % after a single conditioning cycle.

Assuming the conditioning unit operates continuously (24/7) for an entire year (365 days), means that the total energy consumption would be 120.8 MWh. When accounting for the Shelly device's measurement accuracy, would the total energy consumption be:

$$120.810 \text{ MWh} \cdot 1 \% = \pm 1.2081 \text{ MWh}$$
$$120.810 \text{ MWh} + 1.2081 \text{ MWh} = 122 \text{ MWh}$$
$$120.810 \text{ MWh} - 1.2081 \text{ MWh} = 119.6 \text{ MWh}$$

This means that the actual energy consumption of the conditioning unit over one year would range between 119.6 MWh and 122 MWh.

5.2 Second test

The second test for the Shelly Pro 3EM energy meter was conducted to evaluate its current measurement accuracy using the Fluke A3001 FC current measurement device as a reference. The test was performed during another conditioning cycle. Since the Fluke A3001 FC can only measure one phase at a time, three devices were used to measure the current flow in each phase separately. This allowed for individual measurement and analysis of each phase. Measurements were recorded at one-minute intervals, resulting in over 1,600 logged data points for the whole conditioning cycle. When the data was extracted from the Fluke devices, an automatic timestamp and data logging time were included for each minute, ensuring seamless monitoring of the different current measurements. The Fluke device shows current measurement in different stages of the metering process, it shows the highest, lowest and average recorded current and at what time for example the highest current was recorded. The Fluke device also records the start time for the logging of the current and the stop time for one cycle meaning that the consumer can get information on when the logging happened precisely.

When data was extracted from the Shelly device using the dedicated IP address to obtain measurements at one-minute intervals. The timestamps were displayed as numerical values, requiring calculations to convert them into a readable format for easier data analysis and verification (see Figure 11.).

Aside from this issue, the data was generally easy to read and understand. The phases were separated into columns a, b, and c, simplifying data interpretation. However, it is necessary for the user to understand the meaning of each measurement. For example, *a_total_act_energy* represented the total actual energy consumed by Phase A during that interval, such as 30 Wh (see Figure 11.).

timestamp	a_total_act_energy	a_fund_act_energy	a_total_act_ret_energy
1739859660	5.0145	5.0394	0.0000
1739859720	4.8519	4.8767	0.0000
1739859780	4.9696	4.9932	0.0000
1739859840	4.8871	4.9113	0.0000
1739859900	4.9817	5.0059	0.0000
1739859960	4.9569	4.9822	0.0000
1739860020	4.9609	4.9851	0.0000
1739860080	4.9442	4.9673	0.0000
1739860140	4.9609	4.9846	0.0000
1739860200	5.0197	5.0440	0.0000
1739860260	5.0780	5.1040	0.0000
1739860320	4.9090	4.9326	0.0000
1739860380	5.0866	5.1114	0.0000
1739860440	4.9499	4.9753	0.0000
1739860500	5.0105	5.0347	0.0000
1739860560	5.0261	5.0509	0.0000
1739860620	5.0515	5.0763	0.0000
1739860680	5.0151	5.0376	0.0000
1739860740	5.0930	5.1172	0.0000
1739860800	5.0492	5.0734	0.0000
1739860860	5.0468	5.0705	0.0000
1739860920	5.0244	5.0480	0.0000

Figure 11. Screenshot of the data extracted from the Shelly device

The timestamp is displayed in seconds, meaning that the Shelly server began logging data from January 1, 1970, with timestamps recorded in seconds. To convert this into a readable format, the timestamp should be divided by 86400, then 25569 should be added to adjust the time to UTC (time zone 0). An additional 7200 seconds must be added to the timestamp to align the data with Helsinki's time zone (UTC+2). Then the cell format has to be formatted to show time instead of numbers or text. This method ensured accurate data collection with the correct timestamps. (Shelly 3, 2024)

The current measurements indicate that both current meters are functioning properly, as their readings are relatively similar. However, some differences can be observed between

Figure 12., Figure 13. and Figure 14. The Shelly energy meter shows greater fluctuations compared to the Fluke device in all graphs, making the Fluke's data appear more easily readable when exported. This occurs because the Fluke A3001 FC is designed for high-current measurements.

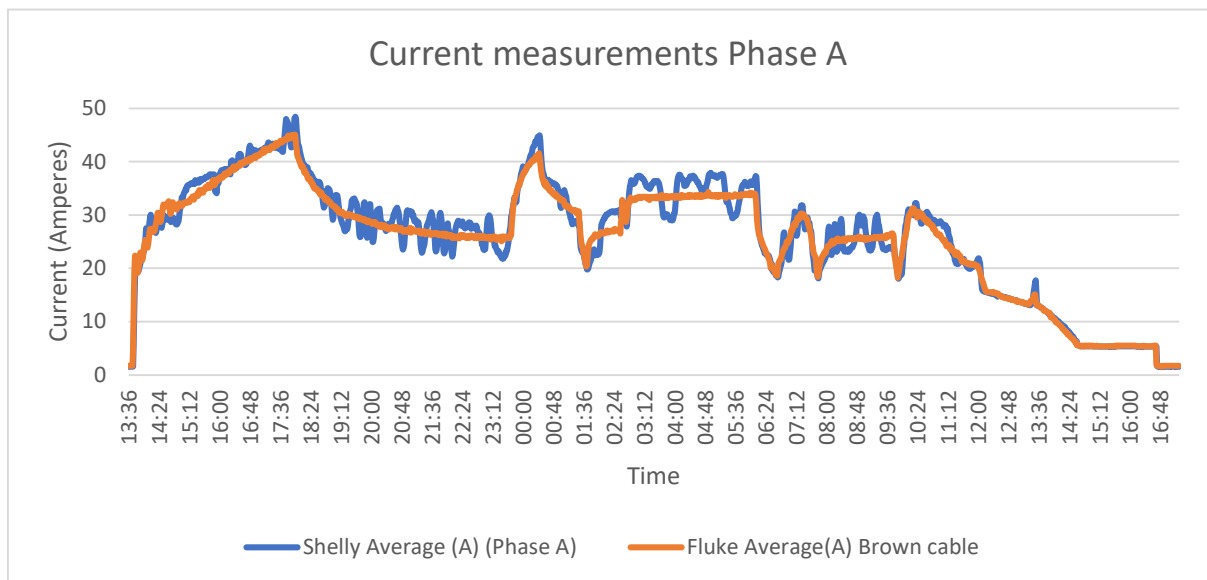


Figure 12. Current measurement difference Phase A

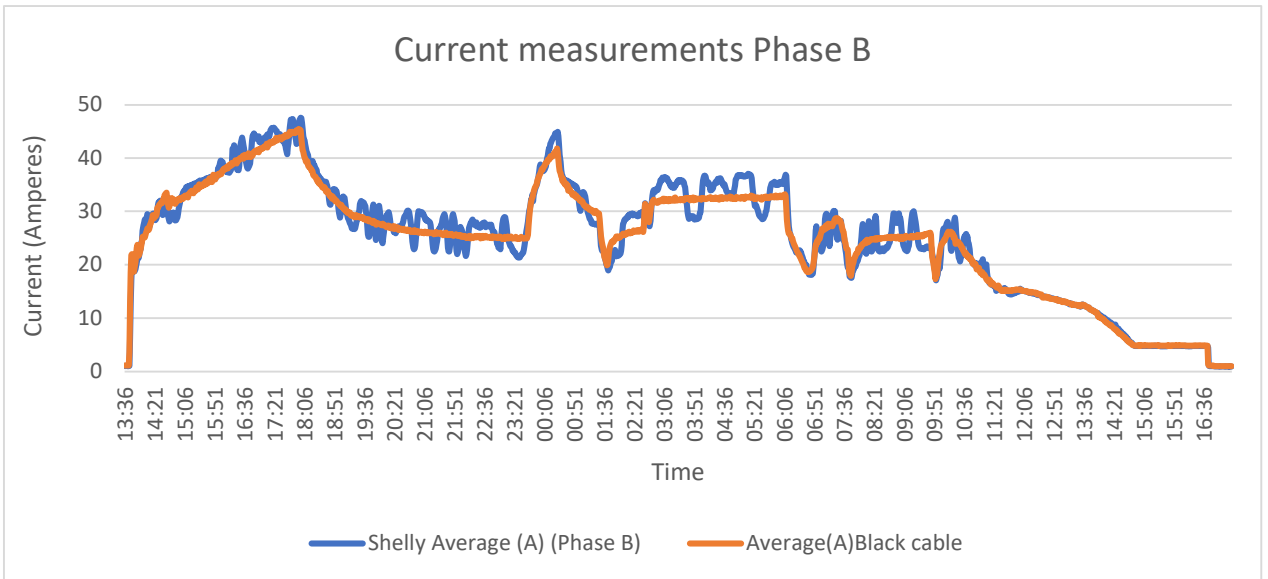


Figure 13. Current measurement difference Phase B

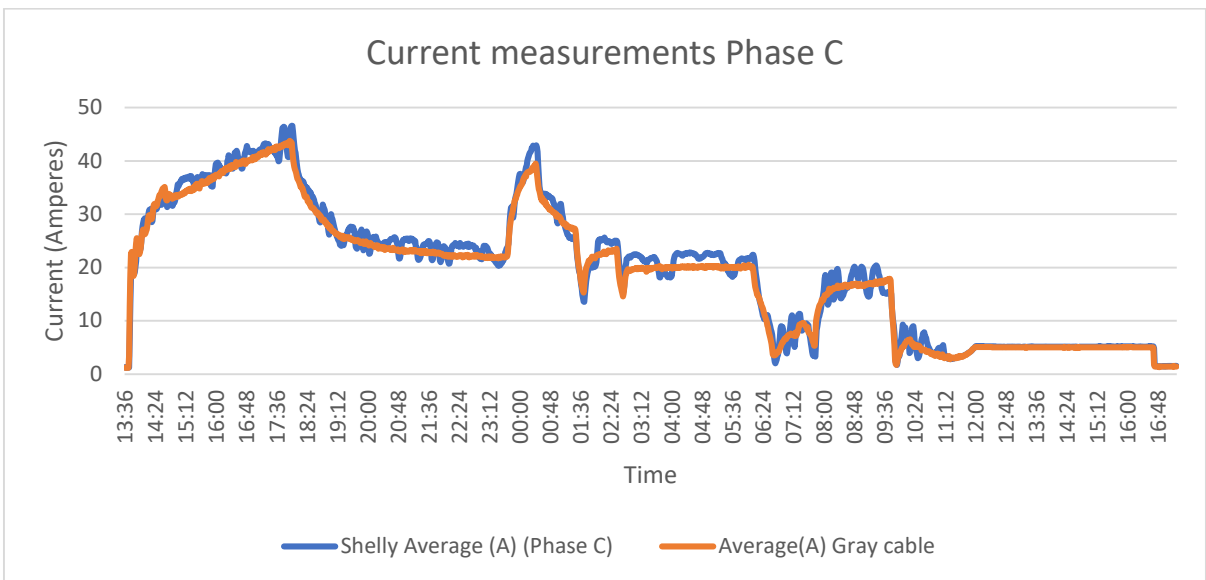


Figure 14. Current measurement difference Phase C

The Fluke device does not measure with the same precision as the Shelly device, which results in more linear readings. In contrast, the Shelly device provides more precise data, measuring all fluctuations in the current caused by the conditioning machine, which leads to further variations in its readings every second. Meanwhile, the Fluke averages its measurements, producing a cleaner graph. Upon closer investigation of Figure 13. and Figure 14., differences in current consumption across the phases can be observed. This means that different phases have different power consumption.

6 Summary

The objective of this thesis was to select and implement an energy monitoring system in which energy consumption could be tracked and data collected for sustainability reporting, LCA analyses, and future optimizations of high-energy-consuming devices. The thesis examines various energy meters, their operation, potential limitations in implementation, and key considerations when selecting an energy meter for consumer use. Additionally, the importance of measurement accuracy is explored, including how to calculate the correct accuracy of a measurement device. Different classes of energy meters are also discussed, such as current transformers, which utilize various measurement technologies, including wound, bar and window-type transformers.

A product comparison is presented, highlighting the features of different energy meters and the expected price ranges for energy monitoring devices. The comparison also examines the IoT-based logging capabilities of these devices, demonstrating the future of energy monitoring and the differences in available software options. Price variation is a significant factor in evaluating energy monitoring devices, and a high fluctuation in prices was observed and analyzed. The price comparison serves as a benchmark for consumers, providing an estimate of shelf prices. However, it is noted that actual prices may be lower when requesting a quote.

The testing of the selected Shelly Pro 3EM device was conducted in real scenarios, providing data that could be expected in future applications. However, a more precise reference energy meter would have been preferable for comparison. The test data demonstrated promising results from the Shelly device, confirming that the chosen device was a suitable option for Elcogen's needs.

The data displayed in the Shelly cloud software was easy to understand and monitor, offering consumers a realistic expectation of the device's performance. However, the extracted CSV data could have been more user-friendly. Making the timestamps readable and understandable remains a manual process that needs to be addressed when extracting data.

6.1 Further development work

Twelve new Shelly devices have been ordered, along with thirteen neutral current transformers to enable neutral phase measurements. These Shelly energy meters will be installed to monitor the remaining conditioning devices and material testing ovens, allowing for better oversight of high-energy-consuming equipment. Additionally, a user guide will be created to facilitate future installations and usage, making it easier to integrate new Shelly devices. Once the new measurement devices are installed, they can be organized in the Shelly Cloud application to reflect their specific usage areas. For example, the conditioning area would include only the conditioning stations and compressors, allowing the total energy consumption of the room to be displayed more clearly. This will simplify the monitoring of energy usage in specific areas.

7 Sammanfattning

EU:s klimatpolitik bygger på tidigare avtal som FN:s klimatkonvention, Kyotoprotokollet och Parisavtalet. Målet är att minska växthusgasutsläppen med 55 % till 2030 jämfört med 1990 och uppnå koldioxidneutralitet senast 2050. EU:s utsläppshandelssystem (EU ETS) ska minska utsläppen med 62 % från 2005 års nivåer till 2030. Det omfattar stora industrier, sjöfart, kraftverk och flyg inom europeiska ekonomiska samarbetsområden. Finland siktar på att minska utsläppen inom transport, jordbruk, byggnadsuppvärmning och avfall med 50 % till 2030 (jämfört med 2005) och uppnå koldioxidneutralitet redan 2035. (Ympäristöministeriö, 2024)

Elcogen följer ISO 14001 standarden och vill optimera sin energianvändning med hjälp av ett energimättnings system. Detta examensarbete handlar om att planera och testa ett system för kontinuerlig energimätning för framtida förbättringar inom energikonsumtion (ISO, 2015). Elcogen är ett europeiskt “cleantech” företag, grundat 2001, som specialiserar sig på solidoxidteknologi. Företagets SOFC- och SOEC-lösningar kännetecknas av hög effektivitet, flexibilitet och reversibilitet. Med driftstemperaturer så låga som 650°C uppnår Elcogen’s bränsleceller en verkningsgrad på över 75 % och möjliggör vätgasproduktion med endast 33 kWh/kg. Elcogen erbjuder tre huvudprodukter solidoxidceller, plana, keramiska och anodstödda celler (600–800°C) se Figure 1. Solidoxidstackar, kostnadseffektiva stackar för massproduktion se Figure 1. Stackmoduler, inkluderar kompressionssystem, gasfördelning och luftdistribution se Figure 1. Med huvudkontor i Tallinn och Vanda betjänar Elcogen en global kundbas i över 30 länder. Företaget är en förebild inom solidoxidteknologi och bidrar till en hållbar, koldioxidfri energiframtid. (Elcogen, 2024)

Elcogen följer ISO 14001-standardens för miljöledning, vilket innebär att företaget ständigt ska förbättra och utveckla strategier för att minska sin miljöpåverkan. Målen sätts av Elcogen’s egen ledning, vilket skapar ett starkt internt ansvar för att följa upp energihanteringsstrategierna. Elcogen implementerar ett nytt energimättnings system för maskiner med hög energiförbrukning, som konditioneringsenheter och materialtestugnar. Dessa system kan nå temperaturer upp till 850 °C och används vid tester som pågår i

hundra- eller tusentals timmar. Genom att mäta energiförbrukningen kan Elcogen identifiera möjligheter till framtida optimeringar som följer ISO 14001 standarden. (ISO, 2015)

Detta examensarbete kombinerar litteraturstudier och kvantitativa forskningsmetoder. Litteraturstudien omfattar produktinformation, tekniska datablad för energimätare, konditioneringsenheter och testugnar samt material från olika källor, inklusive Elcogen. Kvantitativ forskning ger numerisk data som analyseras och visualiseras med hjälp av diagram. Målet är att analysera och jämföra olika energimätningssystem. I detta lärdomsprov kommer tekniska datablad för att bedöma energibehovet hos konditioneringsenheterna och testugnarna användas, därmed kan man identifiera det mest lämpliga systemet för Elcogen. Efter installationen kommer utvärdering av systemets prestanda och idéer för framtida lösningar föreslås.

För att mäta energiförbrukningen hos energikrävande maskiner krävs energimätare som kan övervaka i realtid under längre tids perioder. DIN-skenmonterade energimätare är särskilt lämpliga tack vare sin tillförlitlighet, kompakta design och enkla underhåll, vilket gör dem idealiska för Elcogen's behov (Chint Global, 2022). Vid val av energimätare prioriterar Elcogen tillförlitlighet, mätnoggrannhet och enkel datainsamling. Mätarna måste klara ström upp till 125 A, för att hantera konditioneringsenheternas höga förbrukning. Vanliga noggrannhetsklasser är 0.1, 0.2, 0.5 (C), 1 (B) och 2 (A), som anger procentuell mätosäkerhet (Eastron, 2024). Enligt direktiv 2014/32/EU får lätt industri använda mätare av klass B, vilket gäller för Elcogen (EUR-Lex, 2014) (Iea, 2023). Alla granskade mätsystem i denna avhandling har noggrannhetsklass B, som har mätosäkerhet på ± 1 % för ström, och i den sällsynta fallet att energimätaren kan mäta spänning, har den också en mätosäkerhet på ± 1 %. (Shellykauppa, 2024)

Handhållna mätinstrument är avsedda för kortvarig användning och är därför olämpliga för långsiktig, kontinuerlig energimätning. Eftersom de oftast drivs av batterier begränsas deras kapacitet ytterligare för långtidsövervakning. Vid testning kommer Fluke a3001 FC att användas som referens för noggrannhet. Fluke är en välkänd tillverkare av

mätinstrument med lång erfarenhet, och Elcogen har tidigare använt denna modell för energimätningar. Fluke a3001 FC har en mätnoggrannhet på $\pm 3\%$. (Fluke, 2025)

DIN-skenmonterade mätinstrument installeras i elskåp och är ständigt anslutna till elnätet, vilket möjliggör kontinuerlig energimätning. Vid val av mätare är det viktigt att avgöra om ett strömtransformatorbaserat eller direktanslutet instrument passar bäst. Strömtransformatorer omvandlar höga strömmar till hanterbara nivåer och används främst i industrin, medan direktanslutna mätare ger högre noggrannhet men klarar oftast bara strömmar upp till 100 A, vilket gör dem vanliga i hushåll och små företag. (Polycase, 2020)

Strömtransformatorer sänker primärström till en standardiserad sekundärström, ofta 5 A, med fasta förhållanden som 100/5. Det finns tre typer: lindade transformatorer med separata lindningar (se Figure 2.), fönstertyp där primärledaren går genom ett "fönster" (se Figure 3.), och stångtyp med en fast metallstång för höga strömmar (se Figure 4.). Direktanslutna mätare, ofta shuntbaserade, används för sin noggrannhet men det krävs en strömtransformator vid strömmar över 100 A. (ElectronicsTutorials, 2025) (Roderick, 2021)

För förbättrad energimätning kan IoT-produkter användas. De möjliggör fjärrövervakning av energiförbrukning i realtid och kan automatiskt skicka data till en server för att identifiera avvikelser. En sådan lösning skulle vara idealisk för Elcogen då den förenklar datainsamling och optimering av energianvändningen.

Energi mätarna som undersöks i detta lärdomsprov är: Shelly Pro 3EM är en kompakt och kostnadseffektiv energimätare med noggrannhetsklass B ($\pm 1\%$). Den använder IoT-teknik för molnbaserad datalagring och visualisering, men saknar LCD-skärm. (Shelly 1, 2025) Carlo Gavazzi EM330 har samma noggrannhet och teknik men kräver en datalogger för IoT-anslutning. Den har en LCD-skärm men kräver extra installationsutrymme och separat köp av strömtransformatorer. (Onninen 1, 2025)

ABB B24 liknar EM330 med samma teknik, noggrannhet och behov av datalogger. Även här saknas strömtransformatorer och installationsutrymmet kan vara begränsande. (ABB

1, 2025) ABB D13 använder direktanslutning med samma noggrannhet och krav på datalogger. Nackdelar är begränsad kapacitet för strömmar över 65 A och extra kostnader för datalogger. (ABB 2, 2025)

Elcogen prioriterar användarvänlig och stabil programvara med professionella funktioner. Shelly Cloud möjliggör realtidsövervakning och automatisering av Shelly-enheter, med AI-baserade avvikelsevarningar via en premiumprenumeration (36 €/år) (Shelly 2, 2025). Applikationen är gratis, enkel att använda och ansluts via Bluetooth, AP-sökning eller nätverksskanning (se Figure 5.). EM2 hanterar data från upp till 100 energimätare via en webbaserad plattform. Den lagrar data i upp till 30 år, erbjuder säkerhetskopiering och stöder enkel expansion (Carlo Gavazzi, 2025) (se Figure 6.). ABB InSite liknar EM2 med realtidsövervakning, avvikelsevarningar och stöd för Modbus/OPC för industriell integration (ABB 3, 2025)(se Figure 7.). Samtliga system erbjuder tillförlitlig energimätning och dataexport till Excel. ABB InSite och EM2 är kända för industriell tillförlitlighet, medan Shelly Cloud utmärker sig med sin enkelhet.

Vid jämförelse av priser i Table 1. kommer det fram att Shelly-produkten är mer prisvärd än konkurrenterna. I värsta fall är Shelly-systemet fyra gånger billigare än andra välkända märken. Det innebär att ett komplett Shelly-system för konditioneringsområdet kan köpas för mindre än kostnaden för en enda energimätare + datalogger från ett välkänt varumärke.

Shelly produkten var installerad av en elektriker (se Figure 8.). Installationen var korrekt gjord och produkten fungerade som den skulle. Shelly Pro 3EM testades under en fullständig konditioneringscykel för att säkerställa korrekt funktion. Tidsstämplarna loggades i sekunder från 1 januari 1970 och omvandlades till ett läsbart format med att formatera cellen för att visa tid och månad sedan dividera tidsstämpel med 86400 och addera 25569 för att få tidsstämpeln att visa data i universal tidszon (UTC 0), justera tidszonen med att addera 7200 sekunder för Helsingfors tidszon (UTC+2) (Shelly 3, 2024). Mätningarna visade att både Shelly och Fluke A3001 FC fungerade korrekt, men Shelly uppvisade större fluktuationer i alla grafer (Figure 9.). Fluke genererade mer linjära avläsningar genom att jämna ut värdena, medan Shelly registrerade detaljerade

variationer varje sekund. Graferna 1 och 3 visade skillnader i effektförbrukning mellan faserna. Under konditioneringsprocessen loggades all data korrekt, och fluktuationerna berodde på temperaturgivare som styrde resistorerna för att bibehålla en stabil temperatur (Figure 9.). Data visades i en-timmessintervall, motsvarande medelvärdet av en-minutsmätningar enligt tillverkarens specifikationer.

För att utvärdera strömmättningsnoggrannheten jämfördes Shelly med Fluke A3001 FC. Tre Fluke-enheter användes för att mäta varje fas individuellt, vilket möjliggjorde en mer exakt analys. Mätningarna registrerades i en-minuttsintervall, vilket resulterade i över 1600 datapunkter. Vid dataextraktion från Shelly via IP-adressen var tidsstämplarna svåra att tolka och krävde manuell konvertering (Figure 11.). Övrigt var data lättläst, med faserna separerade i kolumnerna *A*, *B* och *C*. Användaren behövde dock förstå parametrarna, exempelvis *a_total_act_energy*, som visade den totala energiförbrukningen för Fas A i Wh (Figure 11.).

Datan som visades i Shelly Cloud-mjukvaran var lätt att förstå och övervaka, vilket gav konsumenterna en realistisk förväntning på enhetens prestanda. Däremot kunde den extraherade CSV-datan ha varit mer användarvänlig. Att göra tidsstämplarna läsbara och lättförståeliga är fortfarande en manuell process som behöver åtgärdas vid dataextraktion.

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