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TECHNOLOGY, COMMUNICATION AND TRANSPORT

ENERGY EFFICIENCY ACROSS YOUR PLANT

A Feasibility Study of an IoT-Based Energy Monitoring System for Industrial Applications

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General

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Abstract

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A Feasibility Study of an IoT-Based Energy Monitoring System for Industrial Applications

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Tetra Pak

Energy efficiency has become a central pillar of sustainable manufacturing, which is driven by two pressure points, rising energy costs and global environmental commitments. In the food and beverage industry where energy intensive operations such as heating, homogenizing, and filling are standard, optimizing energy use is not only a matter of cost savings but also of regulatory compliance and brand reputation.

Tetra Pak is known for its innovative approach to processing and packaging systems, design, develop and provided operational and complex solutions for customers, where automation and digital control systems are already deeply integrated. However, it has been highlighted that a significant gap remains in energy transparency at machine level within an operational facility. Most plants rely on centralized or aggregated energy metering, which provides a reasonable level of insight but lacks the resolution needed to identify inefficiencies at equipment or process level. As a result of this energy optimization efforts fall short, limited by insufficient data and poor visibility into specific energy consumption patterns.

Advancements in IoT (Internet of things) technologies present a robust framework to bridge operational data gaps. Through the deployment of distributed sensors networks and intelligent edge computing devices real-time telemetry can be captured from individual assets across the production environment. When integrated with high performance data analytics platforms and visual systems, this architecture enables the transformation of raw energy consumption metrics into useable / operational intelligence. This change in basic assumptions facilitates a transition which could potentially allow real time analytics of energy data and plant and production level enabling precise monitoring, control, and optimization.

This feasibility study explores the application of an IoT based energy monitoring system tailored for Tetra Pak and its customers who operate their production filling and processing equipment. The proposed solution focuses on cost effective, modular, and scalable technologies that can integrate existing plant automation systems across the plant level from raw product in, through production and out to the packed product. The goal is to demonstrate how detailed machine level energy data can unlock measurable improvements in efficiency, support compliance with standards such as ISO 50001, ISO 14001 and IEC 62443 principle's as well (International Organization for Standardization 2018 International Electrotechnical Commission, 2018) as contributing towards long term sustainability targets.

The study evaluates the potential system from various dimensions, technical, economic, operational legal and environmental. Offering a comprehensive roadmap to a potential solution for implementation. It also will examine key risks and mitigations, outline deployment strategies and provides a "prototype" to demonstrate core concepts.

By focusing on energy efficiency across the plant through the lens of IoT, this work will align with both industry trends and corporate responsibility setting a foundation for smarter and more sustainable production environments.

Keywords
Smart manufacturing; IoT internet of things, energy monitoring, optimization; retrofitting; industrial energy efficiency; Modbus TCP/IP; data-driven decision-making, Retrofitting, data driven decision making

General

CONTENTS

General

List of Images

General

INTRODUCTION

Tetra Pak is a global leader in food processing and packaging solutions, operating in a highly competitive and sustainability driven industry where efficiency, sustainability and operational transparency are becoming increasingly critical to both business competitiveness and regulatory compliance. Rising energy prices, tightening environmental legislation, and growing customer expectations for sustainable production, place continuous place continuous pressure on food and beverage manufactures to better understand and optimize how energy is used throughout their processes. Although Tetra Paks equipment incorporates advanced automation, sophisticated control systems, and high levels of digitalization, one persistent gap across many customer sites is the absence of detailed machine level monitoring of energy consumption.

Most production facilities continue to rely on aggregated plant level or utility level energy metering. This approach is adequate for high level reporting; it lacks the resolution needed to identify where inefficiencies occur within specific stages of the process. Equipment such as pasteurizers, homogenizers, CIP (Cleaning-in-Place) systems, refrigeration units, and high-speed filling machines operate continuously and under varying load conditions. Without granular data, it becomes difficult to link changes in energy use to equipment health, production schedules, operator behaviour, or specific process conditions. As a result, large opportunities for optimization often remain unnoticed.

Current systems often provide coarse energy data making it difficult to pinpoint inefficiencies and allowing production equipment to optimize energy on a “per machine” basis. The food processing industry is one of the most energy intensive sectors, with costs representing 5-20% of total production expenses. Granular monitoring is essential to reduce these costs. (food safety institute ,2024)

The concept explored in this feasibility study is the development of an IoT based energy monitoring layer that integrates alongside Tetra Paks existing automation systems without altering on interrupting with validated process logic. This layer would utilize non-intrusive sensors and industrial IoT gateways or in some cases existing PLC platforms to capture electrical and utility data in real time. Standard communication protocols such as MQTT (message queuing telemetry transport), Modbus TCP/IP and OPC UA Would be used to securely transmit data into a central database or SCADA environment where it can be visualized, analysed, and used to support operational decision making.

To ensure broad compatibility and seamless integration with existing automation environments, the proposed IoT based monitoring system will be designed to work alongside widely used industrial platforms allowing it to be easily integrated at customer sites reducing cost of implementation. Platform examples such as Siemens (TIA portal S7 PLCs, Rockwell Automation Allen Bradley control Logix), Beckhoff (Twin CAT) and Wonderware now AVEVA systems platform. These platforms form the backbone of filling and process control systems and are responsible for managing critical operations across production lines.

Edge devices act as protocol bridges, translating raw sensor data into formats compatible with existing human machine interfaces and SCADA systems. This approach will avoid disrupting core control logic while providing enhanced visibility to energy consumption. Energy KPIs (Key performance indicators) and alerts can be generated into existing operator interfaces allowing insights to be available to customers within a familiar user environment.

Enabling non-invasive, bidirectional communication with established systems; the IoT based monitoring solution will complement existing automation investments, enhance energy transparency, and support a unified approach to optimization and sustainability.

The aim of this study is to assess whether such a system is viable from technical, economic, operational, environmental, and legal perspectives. The technical feasibility section examines suitable hardware, network requirements, integration strategies, communication protocols, data management, and compatibility with Tetra Pak's automation platforms. The economic analysis evaluates implementation costs, potential energy savings, return on investment, and long-term financial benefits. Operational feasibility considers training, user adoption, maintainability, system reliability, and cybersecurity. Legal and environmental considerations focus on regulatory compliance, data protection obligations, sustainability contributions, and alignment with international standards such as ISO 50001 and ISO 14001.

Instead of building a physical prototype, this feasibility study relies on engineering documentation, vendor specifications, practical insights into Tetra Pak production environments, and established industrial case studies. This approach ensures that the proposed solution reflects realistic constraints while maintaining a strong technical foundation. The study aims to determine whether an IoT-based energy monitoring system could meaningfully improve energy transparency, support data-driven optimization, and contribute to both Tetra Pak's and its customers' long-term sustainability and operational performance.

1 BACKGROUND

1.1 Industry Context and Energy Challenges

The food and beverage industry is one of the most energy-intensive sectors within global manufacturing. This is due to its reliance on thermal and mechanical processes that must operate continuously and under strict hygienic conditions. Pasteurization, sterilization, homogenization, cooling, refrigeration, and high-speed filling all demand significant amounts of thermal and electrical energy. In many cases, these operations run around the clock, often at varying loads, and must meet tight process tolerances to ensure product quality and food safety. Figure one shows pasteurization units which consume large amounts of steam and electricity, making them ideal candidates for energy monitoring.

Figure 1. BF Pasteurizer unit used in beverage processing, Source: Author's own photo.

In recent years, manufacturers have adopted various strategies to improve energy efficiency ranging from equipment upgrades and maintenance optimization to utility level energy audits. However, these strategies often fall short of delivering real time, machine level insights, which are necessary for continuous improvement and data driven energy management.

At the same time, energy monitoring systems in many facilities remain centralized and aggregated, providing only plant wide or line level metrics. This lack of granularity makes it difficult to identify underperforming equipment, detect early signs of equipment faults, or link energy usage to specific process anomalies. In effect, customer operators and management are left with a fragmented view of energy performance, hindering progress toward ISO 50001 compliance, cost reduction targets, and sustainability goals.

Tetra Pak, with its global presence in processing and packaging solutions, exemplifies this challenge. While their customer factories are equipped with advanced automation systems, they often lack the necessary instrumentation to track energy usage at the individual machine level. Bridging this gap requires new approaches that go beyond traditional energy saving tactics and into the realm of digitized, real-time monitoring and analytics.

1.2 Objectives

The purpose of this feasibility study is to evaluate whether an IoT-based energy monitoring system can be effectively designed, integrated, and deployed within Tetra Pak processing and filling environments. The study aims to determine if such a solution can provide actionable, real-time data that enhances energy visibility, improves operational efficiency, and supports sustainability targets across diverse production facilities.

The primary objective is to assess the feasibility of capturing, analysing, and visualizing machine-level energy and utility data using modular and scalable architecture. This requires evaluating hardware suitability, communication protocols, system integration pathways, data storage solutions, network requirements, and compatibility with automation platforms already in use across Tetra Pak installations. The specific objectives of the study are to:

- Identify key energy consuming equipment at a customer level in the food and beverage industry who operate Tetra Pak filling and processing equipment, which would benefit from real time energy monitoring.
- Conceptualize a modular and scalable system architecture capable of acquiring, transmitting, and visualizing machine level energy data, exploring existing IoT platforms and protocols.
- Evaluate system performance through simulation modelling.
- Analyse the technical, economic, and operational feasibility of deploying the system across production facilities, considering complex integration, cost benefit ratios, and organizational readiness. Technical feasibility, can it integrate with Tetra Paks existing automation systems? Economic feasibility, what are the estimated costs vs potential savings based on specific energy consumption (SEC)? Operational feasibility Training Tetra and customer? Is there sufficient support? What are the risks?

One of the key metrics used in evaluating energy performance in industrial environments is Specific Energy Consumption (SEC), which quantifies the amount of energy used per unit of product output (e.g., kWh/litre). This metric allows manufacturers to normalize energy use across different machines, products, and production scales. According to a study by the Department of Energy Systems at Linköping University, SEC is particularly effective in identifying inefficiencies and benchmarking energy performance in food and beverage operations (MDPI, 2019). In the context of this feasibility study, SEC will serve as a baseline indicator for evaluating potential energy savings achievable through machine-level energy monitoring and analytics.

General

1.3 Scope

This feasibility study focuses on evaluating the technical and practical viability of implementing an IoT based energy monitoring system with Tetra Pak production environments, The defined scope includes:

- Targeting both upstream and downstream equipment in the production process including energy intensive units such as homogenizers, pasteurizers, filling, and distribution equipment.
- Assess the feasibility of developing a small-scale prototype using representation hardware for example non-invasive energy sensors, edge computing devices and open source or lightweight software platforms. This would include identifying suitable components, creating small PLC source code, estimating integration complexity, and evaluating potential performance based on vendor specifications and comparable case studies.
- Estimating the cost of a basic IoT system, including sensors, edge device, IO communication infrastructure, and data visualization tools.
- Conducting a risk assessment and developing an implementation plan that would consider integration challenges such as network reliability, sensor accuracy and installed equipment base.
- Ensuring alignment with energy management standards, particularly ISO 50001 to support sustainability and regulatory compliance, this is particularly relevant for Tetra Pak because it aligns with their sustainability roadmap.

2 TETRA PAK

2.1. Company

Tetra Pak International S.A. is a privately owned multinational company and part of the Tetra Laval Group, which also includes DeLaval (dairy farming equipment) and Sidel (PET bottle manufacturing). Tetra Pak is headquartered in Pully, Switzerland, with major operations in Lund, Sweden. The company operates in over 160 countries, providing food processing and packaging solutions for dairy, beverages, cheese, ice cream, and prepared foods (Tetra Pak, 2024).

Tetra Pak's net sales reached €12.9 billion in 2024, with 178 billion packages sold globally (Tetra Pak, 2024). The company employs approximately 24,546 people worldwide. Its operations span Europe, Asia, Latin America, and North America, with a strong presence in emerging markets such as India, China, and Africa (Tetra Pak, 2024).

Tetra Pak is committed to sustainability, having earned the EcoVadis Platinum medal-the highest rating for environmental and social responsibility. It was also recognized as one of Europe's best employers (EcoVadis, 2024; Financial Times, 2024).

2.2. Background Information

Tetra Pak was founded in 1951 by Ruben Rausing, based on the tetrahedron-shaped packaging innovation developed by Erik Wallenberg. The company's origins lie in packaging innovation, but over time it has evolved into a comprehensive systems supplier for food production (Tetra Pak, 2024). A major breakthrough was the introduction of aseptic technology, which allowed liquid food products such as milk, juices, and plant-based beverages to be stored safely for months without refrigeration. This innovation reshaped the dairy and beverage industries and established Tetra Pak as a trusted provider of hygienic, efficient, and technologically advanced systems (Company History Report, 2023).

Over the decades, Tetra Pak expanded into a full-service provider of processing equipment, offering solutions such as pasteurizers, homogenizers, UHT systems, mixing and blending systems, heat exchangers, batch and continuous processing lines, cleaning-in-place (CIP) systems, and specialized equipment for cheese, ice cream, and powder handling (Tetra Pak, 2024).

The company is also deeply integrated into factory automation, delivering solutions that rely on Siemens, Rockwell, and Beckhoff control platforms, complemented by SCADA, MES, and digital service tools. This extensive product range positions Tetra Pak at the centre of production environments where energy consumption is one of the largest operational costs (Industry Report, 2024).

The company is also deeply integrated into factory automation, offering solutions that rely on Siemens, Rockwell, and Beckhoff control platforms, complemented by SCADA, MES, and digital service tools. This extensive product range places Tetra Pak at the centre of production environments where energy consumption is one of the largest operational costs.

Tetra Pak's long-standing commitment to innovation and operational excellence makes it well-positioned to integrate new digitalization solutions-such as IoT-based energy monitoring to support customer efficiency, sustainability, and modernization goals.

2.3 Responsibility and Corporate Responsibility

Sustainability is one of Tetra Pak’s core strategic pillars. The company regularly reports progress in its sustainability initiatives, highlighting significant reductions in both operational emissions and emissions across the full value chain. According to Tetra Pak’s most recent sustainability report, the company has achieved more than a 50% reduction in direct operational emissions and approximately a 25% reduction in value chain emissions. These achievements are supported by major investments in renewable and recycled materials, expansion of recycling infrastructure in several markets, and the development of new packaging solutions designed to minimize environmental impact (Tetra Pak, 2024).

The company’s Strategy 2030 emphasizes three key priorities: increasing the use of renewable and recycled materials, improving the recyclability of packaging, and supporting biodiversity through programs such as the Araucaria Conservation initiative in Brazil. From a production-technology perspective, these sustainability goals align closely with improving energy efficiency, reducing resource waste, and implementing ISO 50001-aligned energy management practices across customer facilities. An IoT-based energy monitoring system would therefore not only deliver operational benefits but also reinforce Tetra Pak’s broader corporate sustainability objectives (EcoVadis, 2024).

2.4 Global Installed Base and Operational Diversity

Tetra Pak’s global installed base comprises thousands of processing units, filling machines, and integrated production lines operating under diverse conditions worldwide. These installations range from compact pasteurizers in small dairy operations to fully automated multi-line beverage factories producing hundreds of thousands of packages per hour. As shown in Figure 2, the company’s installed base includes over 113,000 processing units, 8,592 filling machines, and 22,347 downstream equipment units currently in operation, with hundreds of new machines delivered in 2024 alone (Tetra Pak, 2024).

This extensive presence introduces significant variation in automation platforms—including Siemens, Rockwell, Beckhoff, and legacy systems—as well as differences in network infrastructures, utility supply configurations (steam, water, chilled water, electricity, compressed air), local energy prices, consumption profiles, environmental conditions, and operator training and maintenance maturity. Because of this diversity, any proposed energy monitoring solution must be modular, scalable, hardware-agnostic, non-intrusive, and compatible with multiple automation architectures to ensure consistent performance across all environments (Industry Report, 2024).

As shown in Figure 2, Tetra Pak’s installed base includes thousands of machines worldwide.

General

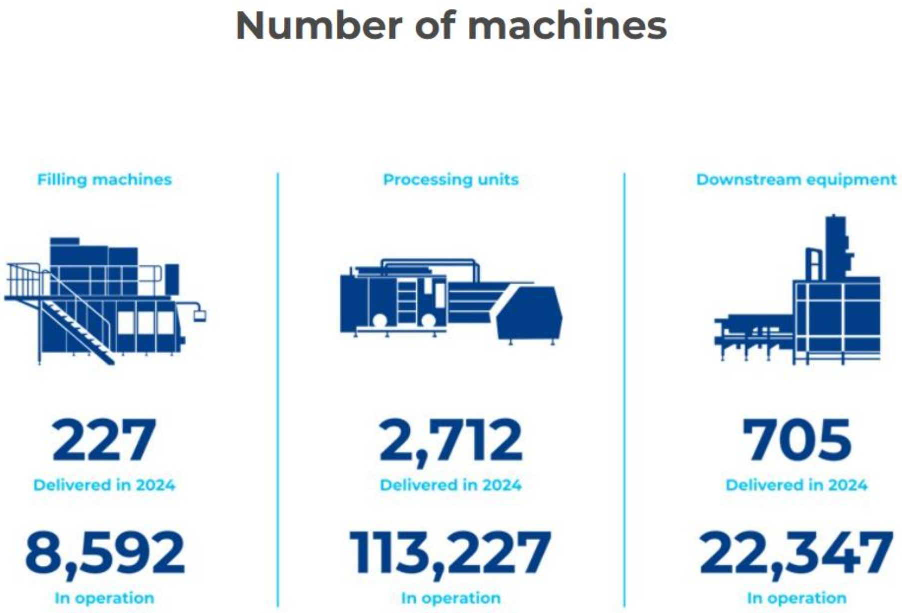


Figure.2 installed base of equipment across the globe 2024 (Tetra Pak,2024).

2.5 Responsibility and Corporate Responsibility.

This combination of advanced processing technology, global presence and strong focus on sustainability makes it an ideal context for evaluating the feasibility of an IoT based Plant to machine level energy monitoring system. The Companies equipment is deeply integrated into production infrastructure where energy consumption is both a major cost driver and area with significant potential for optimization.

3 MARKET & INDUSTRY ANALYSIS

3.1 Overview

This section examines current trends in industrial energy efficiency, the adoption of IoT technologies in manufacturing and benchmark practices from leading companies. The aim is to position the proposed IoT based energy monitoring system within a broader industry development and validate its relevance in both operational and strategic contexts for Tetra Pak and its customer base.

3.2 Trends in industrial energy efficiency.

Globally, industrial sectors account for nearly 40% of total energy consumption, with food and beverage manufacturing among the most energy-intensive segments. This is primarily due to reliance on energy-demanding processes such as heating, cooling, sterilization, and mechanical packaging (International Energy Agency IEA, 2024).

Key drivers of change include increasing regulation of energy use and carbon emissions, corporate commitments to net-zero targets and environmental governance metrics and growing adoption of data-driven energy optimization platforms. According to the IEA, efficiency improvements enabled by better monitoring and control systems can reduce industrial energy use by up to 30%, highlighting the potential impact of machine-level visibility (IEA, 2024).

3.3 Industry and Smart manufacturing

The rise of Industry 4.0 is transforming how manufacturers collect, analyse, and act on production data. Energy monitoring is becoming a foundational element of smart factory strategies, supported by sensors and I/O for real-time machine-level data acquisition, cloud and edge computing for scalable analytics and decision-making, digital twins to simulate and predict energy performance, and AI-driven predictive maintenance to reduce waste and prevent equipment failure (Schwab, 2023).

3.4 Benchmarking Against industry leaders.

Several large manufacturers have already implemented similar machine level energy monitoring or digital optimization strategies across their facilities and have reported significant improvements in efficiency and cost performance. These industry examples illustrate both the feasibility and potential impact of the type of system evaluated in this study.

Coca Cola reported substantial savings (Sattler, 2025) after integrating energy monitoring with production data in their Dutch facilities. By linking consumption with machine states, the company reduced waste associated with idle running, improved set points, and established more accurate energy baselines. These improvements resulted in an estimated 15% reduction in overall energy use within the monitored areas of the plant. operational costs and improve sustainability. For Tetra Pak, these results demonstrate strong alignment with customer expectations and market direction.

Nestlé documented similar improvements (Nestlé Sustainability Reports, 2024) in sites across Germany and Central Europe after deploying digital energy management tools. Detailed monitoring revealed inefficiencies in CIP cycles, underperforming motors, and poor coordination between equipment start-up and production scheduling. Through targeted interventions, Nestlé achieved energy savings of around 12% and improved predictive maintenance capabilities.

Heineken has adopted advanced digital tools (Johnston, 2024), including digital twins and IoT sensors, across several breweries worldwide. These technologies have enabled real time KPIs, early detection of anomalies, and continuous optimization of heating and cooling processes. Reported results include reductions of more than 10% in energy per hectolitre of beverage produced.

The same pattern appears across other manufacturers such as PepsiCo, Danone, Arla, and Friesland Campina, where digitalization projects have demonstrated clear value through improved energy efficiency, reduced downtime, and enhanced process control.

These case studies highlight that energy monitoring and data-driven optimization are not theoretical concepts—they are actively being used by leading manufacturers to reduce operational costs and improve sustainability. For Tetra Pak, these results demonstrate strong alignment with customer expectations and market direction.

3.5 Mark Opportunity for Tetra Pak

The global market clearly demonstrates both the need for and the value of machine-level energy transparency. Tetra Paks' customer base including dairy, juice and plant-based beverage producers face increasing pressure to improve energy efficiency and reduce environmental impact. An integrated energy monitoring system would not only enhance Tetra Paks' internal visibility and performance but also serve as a value-added offering aligned with customer sustainability priorities.

The Marked increasingly favours solutions that are:

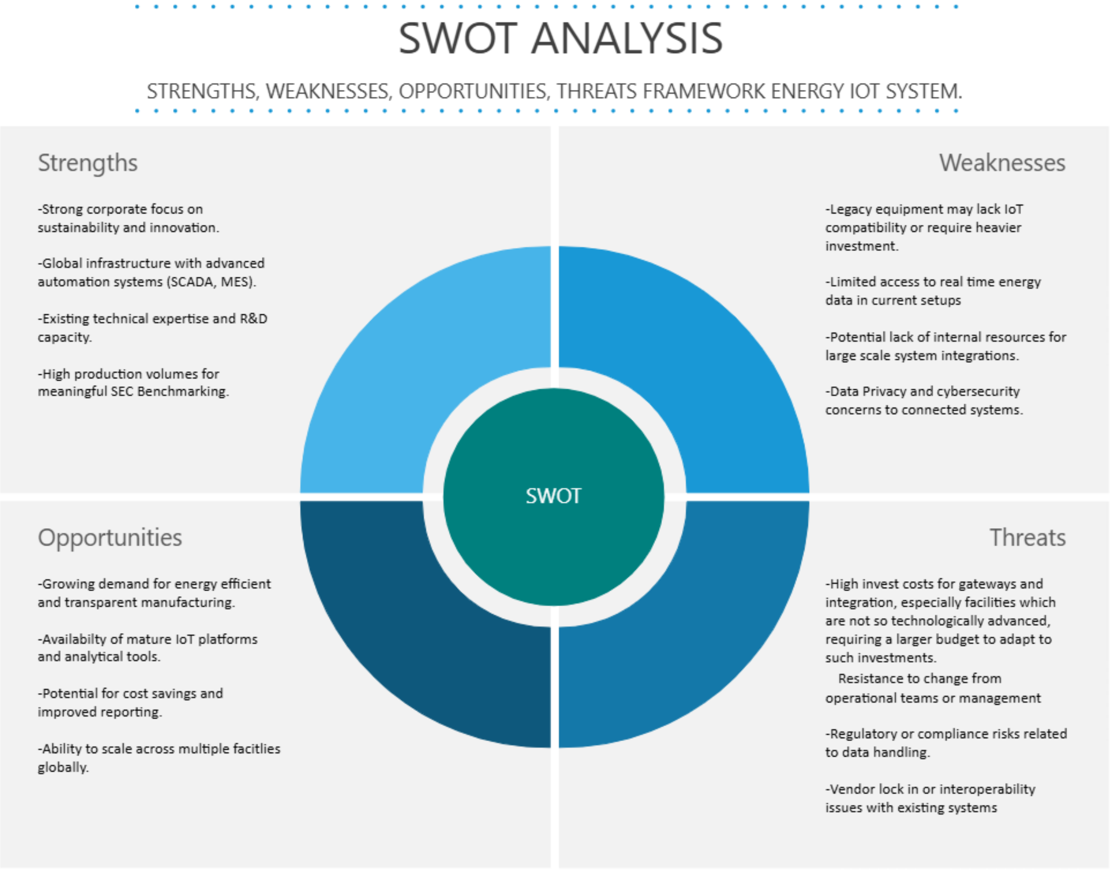
- Modular and scalable.
- Easily integrable into existing automation environments.
- Support corporate sustainability initiatives.

This positions the proposed IoT based energy monitoring systems as both an operational enhancement and a strategic differentiator for Tetra Pak.

3.6 Relevance of industry Case studies to Tetra Pak

The success stories from Coca-Cola, Nestlé, and Heineken illustrate how leading food and beverage companies are leveraging IoT-based systems to reduce energy consumption, improve transparency, and support corporate sustainability initiatives. Tetra Pak can achieve similar benefits by gaining machine-level visibility into energy use, enabling data-driven performance benchmarking across production lines, and aligning energy management with broader goals in production, maintenance, and environmental sustainability. These examples provide practical validation for the feasibility and strategic value of the proposed system.

To further evaluate this potential, a SWOT analysis was conducted to assess Tetra Pak's internal capabilities and external market conditions (Figure 4). The analysis highlights strong corporate commitment to sustainability and global infrastructure as key strengths, while identifying challenges such as legacy equipment and cybersecurity concerns. Opportunities include growing demand for energy-efficient solutions and scalability across multiple facilities, whereas threats relate to high implementation costs and regulatory compliance risks. This strategic assessment reinforces the alignment between industry best practices and Tetra Pak's ability to implement an IoT-based energy monitoring system effectively.



SWOT ANALYSIS

STRENGTHS, WEAKNESSES, OPPORTUNITIES, THREATS FRAMEWORK ENERGY IOT SYSTEM.

Strengths

-Strong corporate focus on sustainability and innovation.

-Global infrastructure with advanced automation systems (SCADA, MES).

-Existing technical expertise and R&D capacity.

-High production volumes for meaningful SEC Benchmarking.

Weaknesses

-Legacy equipment may lack IoT compatibility or require heavier investment.

-Limited access to real time energy data in current setups

-Potential lack of internal resources for large scale system integrations.

-Data Privacy and cybersecurity concerns to connected systems.

Opportunities

-Growing demand for energy efficient and transparent manufacturing.

-Availabilty of mature IoT platforms and analytical tools.

-Potential for cost savings and improved reporting.

-Ability to scale across multiple facitlies globally.

Threats

-High invest costs for gateways and integration, especially facilities which are not so technologically advanced, requiring a larger budget to adapt to such investments.

Resistance to change from operational teams or management

-Regulatory or compliance risks related to data handling.

-Vendor lock in or interoperability issues with existing systems

Figure 3. SWOT analysis of IoT-based energy monitoring implementation for Tetra Pak. (Source: Author’s own analysis).

4 TECHNICAL FEASIBILTY

4.1 Overview

Building on this analysis of industry trends the next section evaluates the technical feasibility of an IoT based energy monitoring system rests on its ability to accurately measure, process and communicate real time energy and utility data in a way that is reliable, non-intrusive, and compatible with a Tetra Pak diverse automation ecosystem. This section examines the proposed architecture in depth, including hardware selection, measurement technologies, communication protocols, integration strategies, data management, cybersecurity, and the overall system workflow.

Because Tetra Pak equipment represents a wide range of generations, control platforms, and utility configurations, the monitoring system must be flexible enough to support legacy systems while also being compatible with the latest automation technologies. The system must also operate independently of core process control logic to maintain validated operation, uptime, and safety requirements. For this reason, the proposed solution is designed as an overlay, meaning it passively observes and collects data but does not interfere with machine operation.

Figure 4 illustrates a schematic layout of a typical dairy process line, which serves as the operational context for the proposed IoT-based energy monitoring system. Understanding this workflow is essential for identifying integration points for sensors, data acquisition modules, and communication interfaces within the production environment.

The following subsections evaluate the technical design in detail, demonstrating that the system can reliably meet the demands of continuous food and beverage production environments.

The focus is on ensuring that the proposed system aligns with the operational requirements, environmental conditions and technical standards typically found in filling and processing facilities.

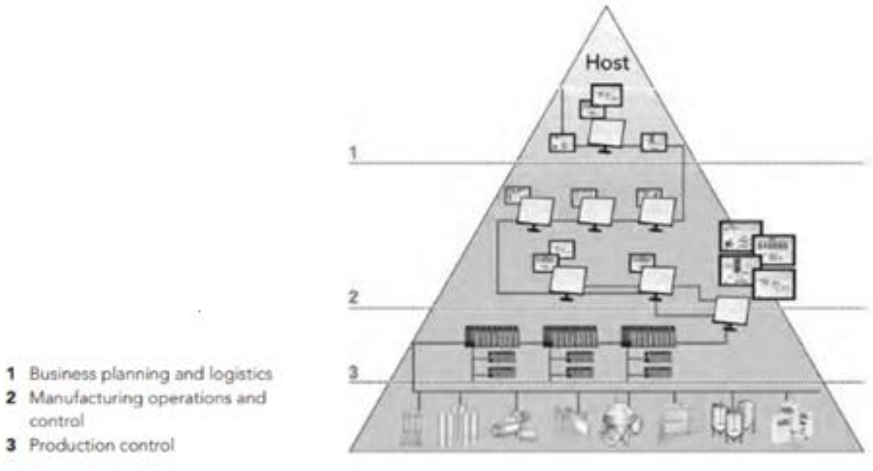


Figure 4. Schematic layout of a complete process line (adapted from Tetra Pak Dairy Processing Handbook).

4.2 System Architecture

The proposed energy monitoring solution uses a layered architecture that separates measurement, processing, communication, and data storage into four distinct functional blocks. This modular approach provides scalability ensuring easier maintenance and long-term adaptability:

Layer 1 Sensor Layer: Capture real time information such as electrical parameters, primarily current and voltage using non-intrusive, DIN rail mountable current transformers and voltage transducers. These are installed on high consumption asses such as homogenizers, pasteurizers, filing equipment and utility systems.

Layer 2 Edge computing layers: Industrial IoT gateways and embedded controllers can perform local preprocessing, data validation, buffering and secure transmission. In scenarios requiring deeper integration PLCS such as Siemens S7 1500 or Rockwell's Compact Logix may serve as edge devices.

A key function at edge level is the real-time calculation of Specific Energy Consumption (SEC), which can be defined as shown in Figure 5. SEC represents the ratio of energy used to the amount of product produced, providing a normalized metric for benchmarking energy performance across machines and processes. Figure 5 also highlights factors influencing SEC, such as system boundaries, production rate, and environmental conditions (MDPI, 2019).

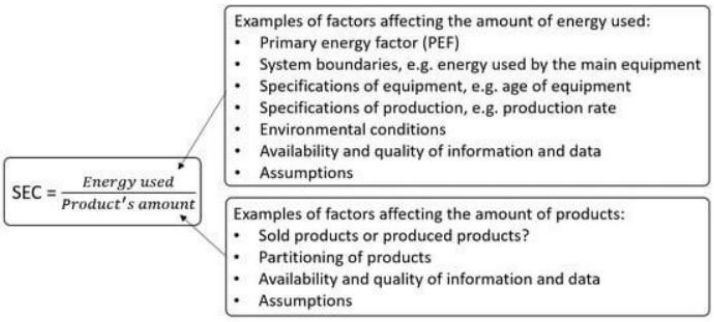


Figure 5. SEC calculation and influencing factors (adapted from MDPI, 2019). Retrieved from https://www.mdpi.com

This metric is computed by synchronizing energy data with production counters or digital signals from packaging and processing equipment. While it enables real-time calculations of energy per package, the same data architecture supports additional performance indicators such as energy per batch, energy per litre, steam or water usage per unit, and carbon footprint per product.

This flexibility allows the system to deliver granular insights across various production modes, utility types, and sustainability KPIs, thereby enhancing value beyond packaging efficiency alone (MDPI, 2019).

Layer 3 Communication infrastructure: Employs lightweight, industry standard protocols such as MQTT and Modbus TCP/IP for real time data exchange. OPC UA is considered for enterprise level interoperability and cyber security.

Layer 4 Backend and visualization layer: Data is stored in a server environment which will serve best compatibility with windows-based IT systems and support robust query performance. For visualization, the system offers flexibility between traditional SCADA platforms such as Intouch, WinCC and modern web browser-based dashboards adapting and building on engineering stations. This approach enables both real time monitoring in control rooms and remote access for energy analysis and management.

4.3 Thermal and Utility monitoring

Beyond electrical energy the proposed system is designed to monitor auxiliary utilities critical to Tetra Pak equipment operations, including steam, water, and cooling energy. These utilities significantly influence overall energy intensity and are essential for calculating Specific Energy Consumption (SEC) across different production modes. Additionally, the Cleaning-in-Place (CIP) process is monitored for cycle duration, utility consumption, and load characteristics. This multi-utility approach enables a more comprehensive and accurate analysis of SEC, supporting targeted energy optimization strategies.

Measuring these utilities requires specialized instrumentation such as steam flow meters (vortex, differential pressure, or ultrasonic), chilled water flow and temperature sensors, compressed air flow meters, pressure transmitters for steam and utility circuits, and temperature sensors placed at critical process points. Most utility measurements can be installed with minimal disruption, as many manufacturers offer clamp-on or insertion-based meters that avoid cutting or modifying existing piping (Industry Report, 2024).

4.4 Industrial Hardware and Device Selection

Hardware selection prioritizes industrial reliability, compatibility with existing automation systems and ease of retrofitting equipment, key considerations include:

Sensors and measuring devices: such as certified split core current transformers and voltage transducers compliant with IEC standards. These support diverse load profiles and can be installed without equipment shutdown.

Edge devices: In the proposed implementation Rockwell CompactLogix PLCs serve as the primary edge devices acquiring energy related data directly from sensors and transmitting it to a central PC at customer level for processing, storage, and visualization. This approach leverages automation infrastructure minimizing the need for additional hardware and simplifying integration.

However, it is important to note that Tetra Pak production lines may differ significantly in terms of equipment type, control architecture, and available interfaces. Therefore, the system design must remain elastic and modular, allowing for alternative edge configurations and integrability. In these cases, such DIN rail mountable industrial IoT gateways available by Siemens or Beckhoff or other embedded controllers may be deployed to perform local data acquisition, preprocessing and secure transmissions. These devices offer rugged design wide operating temperature ranges and support ethernet, Wi-Fi and fieldbus protocols making them also a viable choice for harsh industrial environments.

This flexibility ensures that the energy monitoring system can be tailored to the specific requirements of each production line whether it involves legacy equipment varying utility configurations or different automation platforms.

4.5 Communication protocols and network infrastructure

The proposed system is designed to operate on standard factory Ethernet networks with minimal bandwidth requirements. MQTT's lightweight protocol design ensures efficient high-density data collection, while Modbus TCP/IP provides practical real-time data exchange due to its widespread support within Tetra Pak's existing automation infrastructure. This compatibility minimizes integration complexity and ensures reliable communication across diverse production environments.

For cases requiring standardized data exchange and enhanced cybersecurity, OPC UA is recommended. OPC UA offers platform independence and is relevant in ISO 50001-compliant environments or where integration with enterprise-level systems such as MES (Manufacturing Execution Systems) is required (Industry Report, 2024).

The network infrastructure supports both wired and wireless communication depending on physical layout and environmental constraints, with wired connections preferred for accuracy. Edge devices and PLCs are configured to buffer data locally, ensuring resilience against temporary network disruptions and preventing data loss during transmission failures.

Key network requirements include establishing a local subnet for edge devices, configuring DHCP or static IP addresses, implementing firewall and VLAN settings according to plant IT policies, and securing outbound traffic using TLS encryption. These measures ensure robust connectivity and compliance with cybersecurity standards (Industry Report, 2024).

This flexibility in protocol strategy allows the system to adapt to varying production setups, ensuring compatibility with legacy equipment while supporting future scalability and integration with modern IT systems.

Figure 6 illustrates the proposed system architecture, showing how sensors, PLCs, and factory switches interconnect to enable real-time energy monitoring through SCADA/IoT platforms.

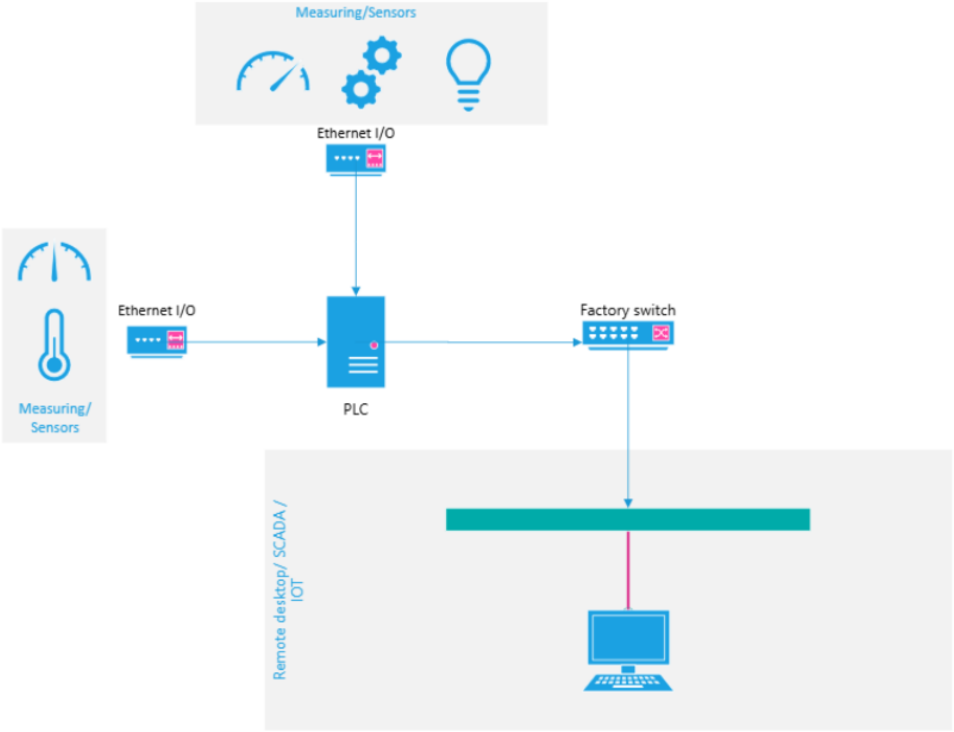


Figure.6. Proposed system architecture for real-time energy monitoring. (Source authors creation).

4.6 Software Stack and data management

The software stack would be designed to ensure reliability, extensibility and seamless integration with industrial IT infrastructure while remaining adaptable to diverse automation environments found across Tetra Paks production equipment. In systems utilizing Rockwell Control and CompactLogix or Siemens S7 PLCs, data acquisition and preprocessing are handled directly within native programming environments like Studio 5000 and TIA portal. These platforms rely on industrial programming languages like ladder logic, structured text and function blocks, all standard across the food and beverage industry.

Once measured and collected, energy or utility data is transmitted from the PLCs to a central PC or server using industrial communication protocols such as Ethernet /IP, Modbus TCP/IP, or OPC UA. The choices of protocols depend on the integration depth and specific configuration of the production line at customer level.

Upon arrival at backend the data is stored in a relational SQL database typically Microsoft SQL server which supports structured queries, long tern retention with enterprise systems like MES (Manufacturing execution systems) this database layer enables historical analysis, audit readiness and flexible reporting across multiple production shifts and utility types.

AS for visualization and analytics the system could utilize software such as Intouch or Microsoft BI to create simple and dynamic dashboards or even be available across a web browser-based platform. The ability to have such dynamic dashboards allows tracking of key performance indicators in real time. Metrics such as energy consumption per machine, power factor and batch level energy use could be continuously monitored. The platform should give alerts and support trend analysis, customizable reports enabling proactive energy and continuous improvement. For operator level visibility, integration with SCADA platforms such as Intouch or WinCC ensure that energy KPIs are displayed alongside production data in a control environment.

This architecture supports both centralized and distributed data management strategies making it suitable for a wide range of production setups and IT policies across Tetra Pak and its customer base. It also allows for future scalability, including the potential integration of additional protocols or historian platforms depending on site specific requirements.

4.7 Integration with Tetra Pak systems

The proposed energy monitoring system is designed for seamless, non-intrusive integration with Tetra Pak’s existing automation infrastructure, including platforms based on Siemens, Rockwell, and Beckhoff. It supports both direct and indirect data exchange with SCADA and MES systems using standardized industrial communication protocols such as OPC UA, Modbus TCP/IP, and MQTT. These protocols enable reliable and secure transmission of sensor and equipment data across various network topologies. Depending on the deployment scenario, data is either transmitted to a central PC server via these protocols or logged locally using SQL-compatible interfaces. Once received, the data is stored in a relational SQL database, typically Microsoft SQL Server, which supports structured queries and integration with enterprise-level systems. The proposed monitoring system integrates seamlessly by running independently of the main PLC cycle, using read-only communication with PLC data blocks, avoiding modification of validated logic, allowing PLCs to share context such as machine state, CIP phase, and product code and supporting both legacy and modern automation architectures.

The architecture supports centralized visualization, real-time analytics, and decision support without introducing new software or hardware layers. It ensures high interoperability, system resilience, and secure data exchange while preserving the integrity of core automation logic. This makes the system technically compatible with a wide range of production setups and IT policies across Tetra Pak environments also reducing the cost of the overall system.

4.8 Validation strategy

As part of the feasibility study, validation will focus on assessing the compatibility of the proposed system architecture with existing Tetra Pak production environments. This includes reviewing hardware interfaces on typical processing and packaging equipment, evaluating communication protocol support across Siemens, Rockwell, and Beckhoff platforms, confirming data availability for key metrics such as energy consumption, production counters, and utility usage, and assessing IT infrastructure readiness, including database servers, SCADA terminals, and remote access capabilities. Rather than constructing a physical prototype, this feasibility study will rely on technical data, engineering documentation, and domain knowledge. This approach aims to confirm that the proposed system can be deployed with minimal disruption, high compatibility, and at a reasonable cost for both stakeholders and customers.

Figure 7 illustrates the conceptual workflow of the proposed architecture, starting from the sensor layer and edge computing devices, progressing through communication infrastructure and SQL backend, and culminating in visualization, multi-utility monitoring, and KPI reporting. This layered design ensures scalability and structured data flow for real-time energy monitoring.

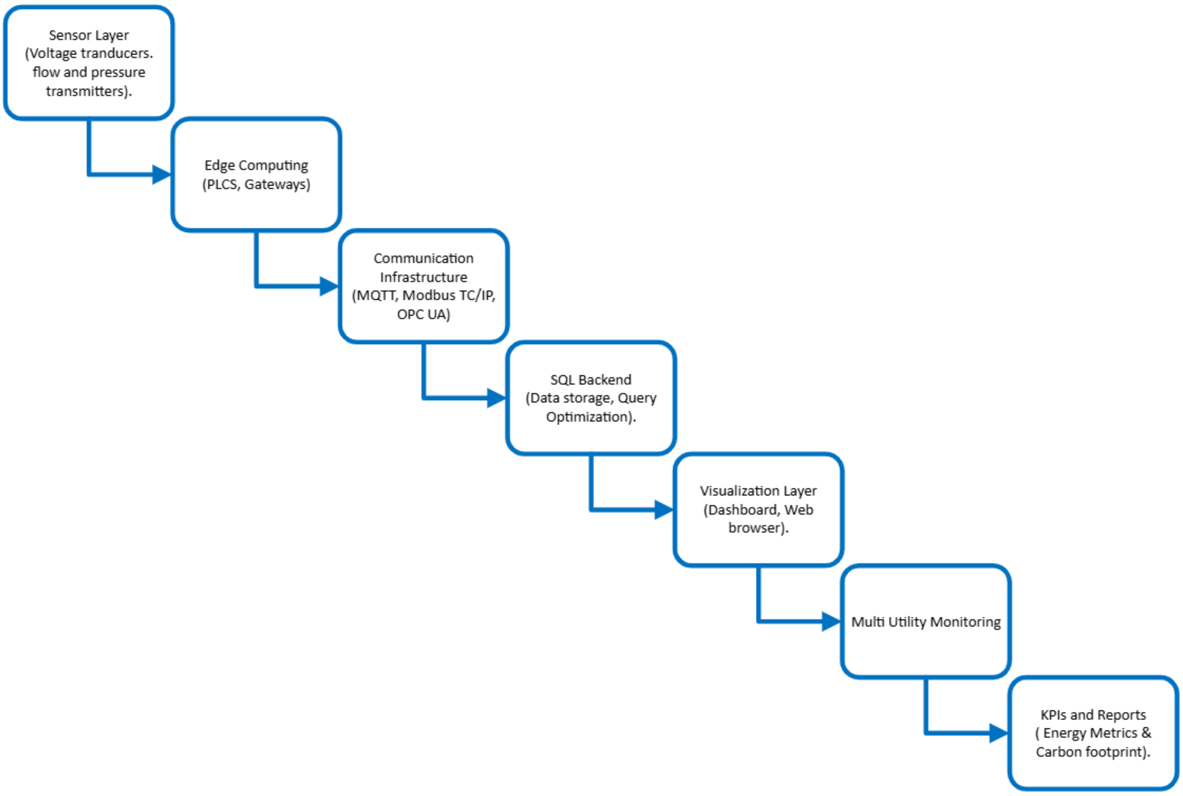


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Figure.7. Structure of the proposed IoT-based energy monitoring system (Source authors creation).

4.9 Technical feasibility Conclusion

The feasibility analysis confirms that the proposed IoT based energy efficiency monitoring system is technically viable for deployment within a Tetra Pak production environment. The architecture leverages industrial grade hardware, standardized communication protocols, and enterprise compatible software tools to ensure robust and scalable performance.

The system would align with operational requirements and industry standards including ISO 50001 and supports integration with existing automation platforms without requiring significant changes to control logic or infrastructure.

Its modular design allows for flexile deployment across diverse production setups including legacy equipment and varying utility configurations.

Based on the findings the system is well suited for pilot implementation in a selected production environment starting with either processing or packaging equipment. Then allowing a clear path to scale across the multiple lines or an entire facility. Architecture is future proof, enabling the integration of additional protocols, historian platforms, and sustainability metrics as operational needs evolve. Figure 8 illustrates a typical integration scenario within a Tetra Pak pasteurizer environment, showing how sensors, PLC modules, communication interfaces, and SCADA terminals interconnect to enable real-time monitoring and data acquisition. This representation validates the compatibility of the proposed architecture with existing hardware and network infrastructure.

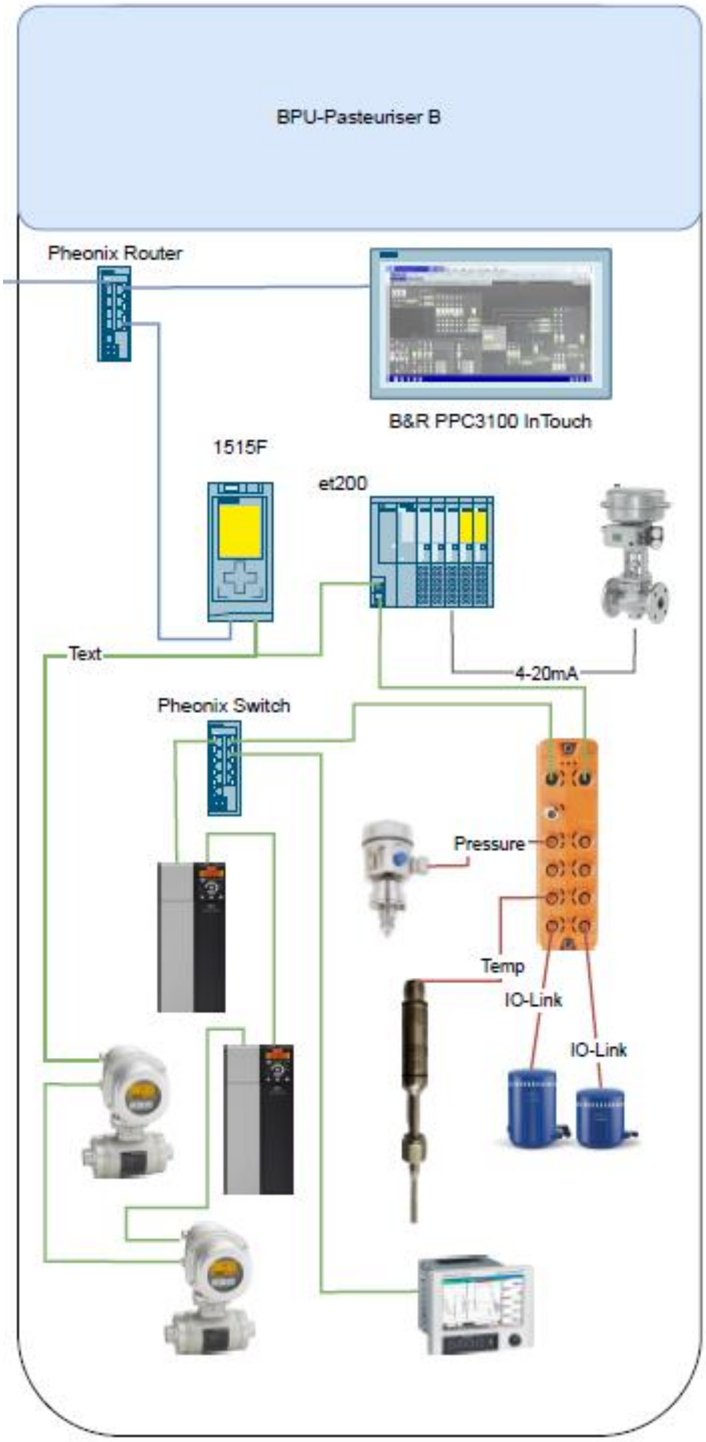


Figure 8. Example of system integration within a pasteurizer environment (Source authors creation).

5 ECONOMIC FEASIBILTY

5.1 Overview

Economic feasibility evaluates whether the proposed IoT based energy monitoring system provides sufficient financial benefit to justify the investment. It is a critical aspect of this study as any decision to implement new technology in an industrial setting must be backed by a clear financial justification. While this proposed IoT based energy monitoring system shows quite strong potential in terms of technical functionality and integration with existing automation infrastructure, its success depends on delivering measurable economic value to Tetra Pak and its customers.

This section provides a detailed evaluation of the costs and projected financial benefits associated with deploying the system at both pilot and full production scales. It will cover all relevant capital operation expenditure including sensor and measuring equipment hardware, industrial edge computing devices, communication infrastructure, software licensing, and integration with existing IT /OT systems. These costs are compared against potential savings resulting from improved energy efficiency, reduced operation waste, and enhanced production transparency.

The analysis considers key financial metrics such as a payback period, return on investment (ROI), and scalability of the solution across a diverse production environment. It draws on benchmarks across the industry and estimated plant level energy consumption data.

The purpose of this section is not only to confirm the systems financial viability but also to demonstrate how it supports broader organizational goals, such as ISO 50001 compliance, reduced total cost of ownership (TCO) and improved service offerings for Tetra Paks customers.

A rollout strategy will be proposed beginning with a pilot installation on limited number of packaging and processing equipment, followed by expansion based on validated performance and ROI.

5.2 Cost structure

The total cost of implementing an energy monitoring system depends on factors such as plant size, number of machines, utility complexity, existing infrastructure, and desired functionality. Costs are divided into two phases: pilot deployment and full-scale implementation. A pilot installation is typically limited to one or two key machines, such as a homogenizer or pasteurizer. The purpose of this phase is to validate sensor performance, verify network integration, confirm data accuracy, and obtain customer alignment before larger rollouts.

The pilot or field test phase focuses on a limited number of machines, with an estimated cost between €15,000 and €30,000. This includes multi-utility sensors for electricity, steam, water, and compressed air on selected assets; industrial IoT gateways such as Siemens IoT2040 or Rockwell edge devices; licensed software tools for data acquisition and visualization (e.g., Power BI Pro and SCADA extensions); integration with existing PLCs and IT/OT systems; professional installation and commissioning; and initial support and calibration services. The pilot is designed not only as a proof of concept but as a fully functional micro-deployment that can be scaled without significant rework. This approach provides validated data for return on investment and supports ISO 50001-aligned reporting from day one.

The full-scale deployment is designed as a modular and customer-tailored solution that allows seamless adaptation to diverse plant layouts, production profiles, and utility infrastructures. This flexibility ensures that each implementation aligns with operational realities and strategic goals of individual production plants. Key components for full-scale deployment include comprehensive sensor coverage across all major assets and utility systems, high-performance industrial edge controllers and IoT gateways for real-time data processing and protocol conversion, full integration with MES, ERP, and enterprise-level dashboards enabling centralized monitoring and reporting, and optional automation upgrades such as Think Top valve retrofits and agitator replacements to enhance process efficiency and reduce utility consumption. Additional energy efficiency enhancements, including heat recovery systems, solar thermal collectors, and other renewable integrations, can also be incorporated. Professional installation, commissioning, and long-term support ensure system reliability and maintainability, while built-in scalability allows future expansion to additional equipment, utility streams, and advanced analytics modules.

The deployment phase delivers plant-wide visibility, predictive diagnostics, and strategic energy optimization while supporting customer-specific objectives such as ISO 50001 compliance, sustainability reporting, and value-added services. Its modular architecture ensures that the system can evolve alongside the facility, accommodating future upgrades and operational changes without disrupting core processes. Importantly, the total cost of a full-scale installation can vary significantly depending on the specific needs of each customer site. Factors such as plant layout, utility infrastructure, equipment types, and desired monitoring depth all influence the final IoT system configuration. Additionally, the system can benefit from incorporating optional upgrade features, including automation upgrades, heat recovery systems, and renewable energy integrations, based on strategic goals and budget availability. This flexibility makes it difficult to provide a single fixed price, but it ensures that each implementation is cost-effective, scalable, and aligned with operational priorities.

5.3 Projected energy savings

Tetra Paks filling and processing equipment are high load systems that operate continuously. Based on industry benchmarks and comparable case studies (Nestlé, Heineken), machine level energy monitoring can yield 10% to 20% savings by identifying inefficiencies such as:

- Idle or low efficiency operating periods.
- Poorly tuned heating and cooling phases.
- Subsystem malfunctions such as underperforming pumps or compressors.
- Shifts based on variations in energy consumption.

Even heating and cooling represent some of the largest energy loads in dairy and beverage processing. Without detailed data setpoints often drift over time or these systems end up operating at much higher than necessary levels.

Machine level data supports:

- Optimizing pasteurization temperatures.

- Reducing overshoots in heating profiles.
- Improving cooling-water control.
- Eliminating unnecessary regeneration losses.

Abnormal increases in power consumption often indicate developing mechanical problems, including:

- Bearing wear.
- Pump cavitation.
- Valve seat leakage.
- Fouled heat exchangers.
- Air leaks in compressed air systems.
- Inefficient refrigeration cycles.

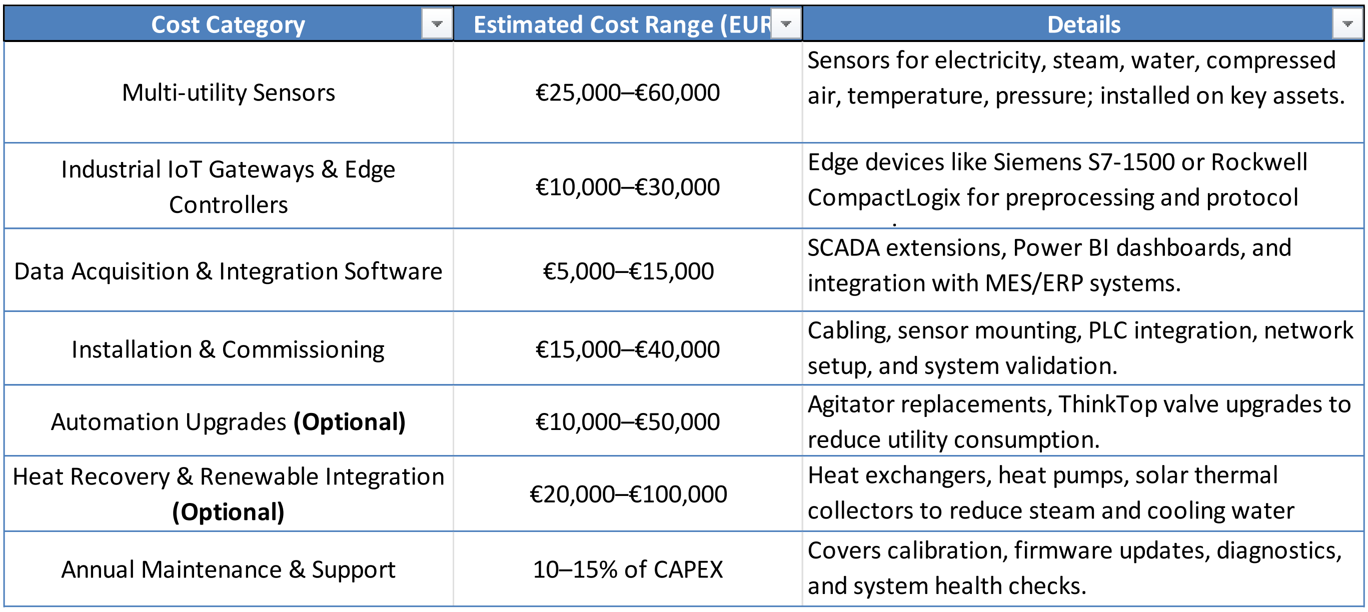
Early detection of mechanical failures reduces both maintenance costs and energy waste.

To illustrate the potential savings, consider a filling line producing one hundred million packs per year, with an average energy consumption of 0,5 kWh per 1,000 packs. At an energy price of €0,20 per kWh, the annual energy cost is approximately €10,000. A 10% reduction in energy use would therefore result in €1,000 in annual savings for that line.

Similarly, for a homogenizer processing ten million litres of milk annually, with a utility cost of €0,50 per 1,000 litres, the total annual cost is around€5,000. A 10% efficiency improvement would yield €500 in savings.

The above estimates suggest that while individual machine level savings appear modest, the cumulative impact across multiple lines and utilities especially when scaled across and entire plant can be substantial. Moreover, the ability to continuously monitor and optimize energy use supports broader goals such as ISO 50001 compliance and reduced total cost of ownership.

Given the typical energy savings (10-20% across monitored loads), the return on investment is favourable.



Cost Category	Estimated Cost Range (EUR	Details
Multi-utility Sensors	€25,000–€60,000	Sensors for electricity, steam, water, compressed air, temperature, pressure; installed on key assets.
Industrial IoT Gateways & Edge Controllers	€10,000–€30,000	Edge devices like Siemens S7-1500 or Rockwell CompactLogix for preprocessing and protocol
Data Acquisition & Integration Software	€5,000–€15,000	SCADA extensions, Power BI dashboards, and integration with MES/ERP systems.
Installation & Commissioning	€15,000–€40,000	Cabling, sensor mounting, PLC integration, network setup, and system validation.
Automation Upgrades **(Optional)**	€10,000–€50,000	Agitator replacements, ThinkTop valve upgrades to reduce utility consumption.
Heat Recovery & Renewable Integration **(Optional)**	€20,000–€100,000	Heat exchangers, heat pumps, solar thermal collectors to reduce steam and cooling water
Annual Maintenance & Support	10–15% of CAPEX	Covers calibration, firmware updates, diagnostics, and system health checks.

Figure.9. Estimated cost ranges for a fully deployed IoT-based energy monitoring system (Source: authors creation).

General

5.4 Scalability and Long-Term Value

The modular nature of the proposed system supports incremental scaling, making it adaptable to a wide range of production environments. Since Tetra Pak lines vary significantly by customer and site, the ability to deploy energy monitoring on high impact equipment first such as homogenizers, pasteurizers, and CIP systems and expand gradually adds economic flexibility and reduces upfront risk.

This approach allows facilities to prioritize assets with the highest energy intensity or operational criticality, validating performance before committing to broader rollout. The system's architecture supports plug and plays expansion, enabling additional sensors, edge devices, and analytics modules to be added as needed.

Additional long-term value includes avoided downtime through predictive maintenance and early fault detection, reduced manual energy audits which save labour and improve accuracy, enhanced ISO 50001 compliance with automated reporting capabilities, and optional value-added services for Tetra Pak clients such as energy analytic dashboards, benchmarking tools, and sustainability metrics.

Because the system is highly configurable total cost of deployment can vary significantly. Factors such as plant layout, utility infrastructure, integration depth, and optional upgrades all influence pricing. This variability makes it difficult to provide a fixed cost estimate, but it ensures that each implementation is strategically aligned, cost-effective, and future ready.

5.5 Economic feasibility conclusion

The economic analysis supports the conclusion that the proposed IoT-based energy monitoring system is financially viable and strategically beneficial. The low capital expenditure for pilot deployment, combined with the potential for 10-20% energy savings, reduced operational waste, and enhanced transparency, makes the system a cost-effective investment.

The approach is especially compelling when implemented first as a pilot, allowing performance validation and ROI measurement before scaling. The system's modular design, compatibility with existing automation platforms, and alignment with ISO 50001 principles further strengthen its long-term value proposition.

The system's modular architecture and scalable cost structure allow pilot testing before full deployment, further reducing financial risk for customers. Overall, the economic feasibility is strong and supports proceeding with pilot installations.

Figure 11 illustrates a process flow diagram for a beverage production plant, showing multiple stages from raw material preparation to filling. This visual representation, adapted from Tetra Pak's Orange Book, highlights the complexity of production environments and underscores the importance of integrating energy monitoring across various process stages to maximize efficiency and savings.

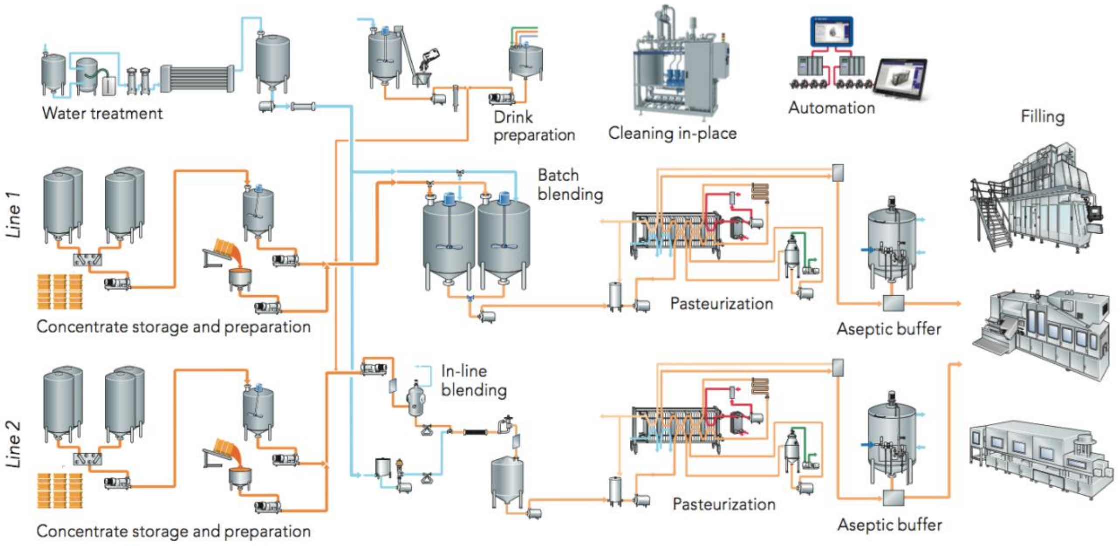


Figure.10. Process flow diagram for a beverage production plant (adapted from Tetra Pak Orange Book).

General

6 OPERATIONAL FEASIBILTY

6.1 Overview

Operational feasibility examines whether the proposed IoT energy monitoring system can function effectively within the daily routines, responsibilities, and constraints of Tetra Pak production environments. Unlike technical feasibility which focuses on hardware, communication, and integration operational feasibility addresses the practical usability of the system, its impact on workflows, maintenance requirements, cybersecurity considerations, and compatibility with existing practices on the factory floor.

Because food and beverage plants operate under strict production schedules, hygiene requirements and uptime expectations, any new system must fit seamlessly into established operations. The system should not increase operator’s workload, jeopardize production, or introduce unnecessary complexity. Instead, it must enhance decision making, simplify analysis, and support continuous improvement with minimal disruption.

An effective monitoring solution depends heavily on its usability. Operators, supervisors, maintenance personnel, and managers must be able to understand and act on the information presented. To support broad adoption, the proposed system uses familiar interfaces and visualization tools that align with current SCADA standards and Tetra Paks existing human machine interface (HMI) conventions.

7.2 Ease of use

Ease of use is a critical success factor in industrial monitoring systems, particularly in environments where operators, engineers and maintenance personnel engage with varying levels of technical complexity. As the proposed system is designed with usability as a core value, enabling plant staff to interpret energy data and take corrective or optimizations actions without requiring advanced analytics expertise.

In production environments, dashboards are developed using more robust SCADA native tools which follow similar standards and layouts of other Tetra Pak equipment interfaces making it more user friendly to operational staff who are already familiar with such user interfaces, this significantly reduces training needs and integration complexity.

The dashboard design supports several practical use cases, such as real time monitoring of energy parameters such as kW, Voltage V, and current A at the machine level as well as the auxiliary utilities including steam, water, cooling media, and compressed air. This multi utility approach will enable comprehensive tracking of energy intensity across various production modes including cleaning in place (CIP) processes.

Fault detection and failure diagnostics to achieve continuous monitoring of energy anomalies, sensor disconnections and abnormal load profiles would allow maintenance teams to respond proactively, reducing downtime and reducing wasted energy.

Intelligent scheduling of energy intensive programs during off peak hours or periods of favourable energy pricing, this feature would support cost optimization and would align with dynamic energy tariff structures and can be integrated with any renewable energy sources production facilities may already have installed.

By providing insight into live energy data the system does not only enhance operational awareness but encourages strategic decision making around energy consumption. The use of intuitive visual elements such as colour coded alerts, trend indicators and status icons ensures that users without data analytic backgrounds can interpret information effectively and respond appropriately.

7.3 Maintainability and technical support

Maintainability is essential for long-term deployment of industrial environments. The proposed IoT based energy monitoring system is designed for operational simplicity, serviceability, and seamless integration with Tetra Paks existing technical infrastructure.

Its modular architecture allows individual components such as sensors.

, edge devices and communication interfaces to be maintained independently without affecting overall system functionality. Industrial hardware, including DIN rail mountable current transformers, voltage transducers and IoT gateways would be selected for durability and compliance with industry standards.

Software maintainability is ensured using widely adopted platforms such as Microsoft SQL server and MQTT. At edge level data acquisition and preprocessing are handled with native PLC environments such as Rockwell’s studio 5000 and TIA Portal by Siemens.

Built in diagnostic capabilities at both hardware and software levels enable automatic detection and logging in faults including disconnected or damaged sensors, network interruptions, and data integrity issues. Alerts can be configured to notify relevant personnel via email or integrated remote service tools.

The monitoring solution can be incorporated into existing remote service computers already deployed at customer sites minimizing the need for additional hardware and aligning with established cybersecurity protocols and remote access policies. Routine tasks such as sensor calibration, firmware updates and software patches can be scheduled along existing maintenance intervals which ensures less additional burden on local staff located at customer sites.

7.5 Reliability and Availability

Reliability is essential in food and beverage production, where unexpected outages can lead to product loss, downtime, and safety hazards. The proposed monitoring system is designed to ensure high availability through the use of industrial-grade hardware and robust network architecture. Local buffering mechanisms guarantee data retention during temporary network failures, while a graceful degradation approach ensures that the loss of the monitoring system does not affect machine operation.

Crucially, the monitoring system operates independently of process control. No PLC logic is modified, no safety functions are altered, and no machine commands are issued. This design principle ensures that even in rare cases of edge-device failure, production continues safely without interruption.

Furthermore, the system’s distributed architecture enhances resilience. If one sensor or gateway fails, the remaining components continue to function normally, maintaining overall system integrity and minimizing operational risk.

7.6 Compatibility with workflows

The energy monitoring system is designed to complement existing plant operations without interfering with core process control activities. It can function as a standalone monitoring layer or be tightly integrated with existing SCADA and MES platforms.

Energy data is made available through standard interfaces including exportable CSV files and optional integration with enterprise resource planning (ERP) systems such as SAP. This flexibility enables energy metrics to be incorporated into production, quality, and maintenance reporting routines used by cross functional teams.

By providing access to relevant data through familiar platforms, the system supports seamless adoption and encourages the inclusion of energy performance in daily decision making.

7.7 IT and Cyber security Considerations

With increasing integration of operational technology and information technology cybersecurity is a critical consideration for any connected system. The proposed solution includes key security features to ensure data integrity and system reliability.

Communication between edge devices and servers is secured using TLS encryption, particularly for MQTT based messaging. Dashboards are protected through password-based authentications and role-based access controls are implemented to restrict access to system parameters.

Production environments utilize Power BI or SCADA integrated displays that follow similar authentication protocols. Additionally, the sensor and edge device network can be isolated from the business IT network using VLAN segmentation or dedicated industrial Ethernet switches.

A deployment checklist covering basic IT hardening practices is provided to ensure consistent and secure implementation across sites.

General

7.8 Operational Feasibility Summary

The proposed IoT system demonstrates a strong operation feasibility for deployment in real world industrial environments. It requires minimal training due to its intuitive dashboards and integration with existing SCADA and remote service interfaces. Its modular architecture supports incremental deployment, while non-intrusive communication methods reduce the risk of operation disruption at production facilities.

Maintenance demands are low and can be incorporated into existing routines. Customizable dashboards built in alerts and robust security measures support.

Operational integration appears feasible with minimal disruption; this leads to the next consideration: identifying potential risks and mitigation strategies.
Figure 11 illustrates a conceptual example of integrating energy monitoring into Tetra Pak’s operator interface. This visualization demonstrates how energy data can be embedded within existing SCADA screens, ensuring seamless operator interaction without requiring major changes to established workflows.

2026 01 30 18.07 PLC_C20C01 Remote Comunication fault PLC_C20C01
2026-01-30 17 53 PLC_C20C02 Remote Comunication fault PLC_C20C02

M01W05	0,4 mS	18,6 °C	0 L/h	0,3 TU	0,0 mS	0,0 °C	FS
M01W04	0,4 mS	18,5 °C	0 L/h	0,1 TU	0,0 mS	0,0 °C	FS
M01W03	0,4 mS	18,2 °C	0 L/h	0,1 TU	0,0 mS	0,0 °C	FS
M01W02	0,4 mS	15,5 °C	0 L/h	0,1 TU	0,0 mS	0,0 °C	FS

CIP Lines Overview

Line	CC#	Cleaning Objects	Recipe	Recipe Step	Step Num	Step Vol	Step Time	Pressure	Press Flow	Press Temp	Ret Cond	Ret Temp	Cond SP	Temp SP		CIP Timer
M01W01											0,4 mS	8,9 °C	0,0 mS	0,0 °C	FS	
M01W02											0,4 mS	15,5 °C	0,0 mS	0,0 °C	FS	
M01W03											0,4 mS	18,2 °C	0,0 mS	0,0 °C	FS	
M01W04											0,4 mS	18,5 °C	0,0 mS	0,0 °C	FS	
M01W05											0,4 mS	18,6 °C	0,0 mS	0,0 °C	FS	

Figure.11. Concept for integrating energy monitoring into operator interface. (Source Tetra Pak).

7 RISK ANALYSIS

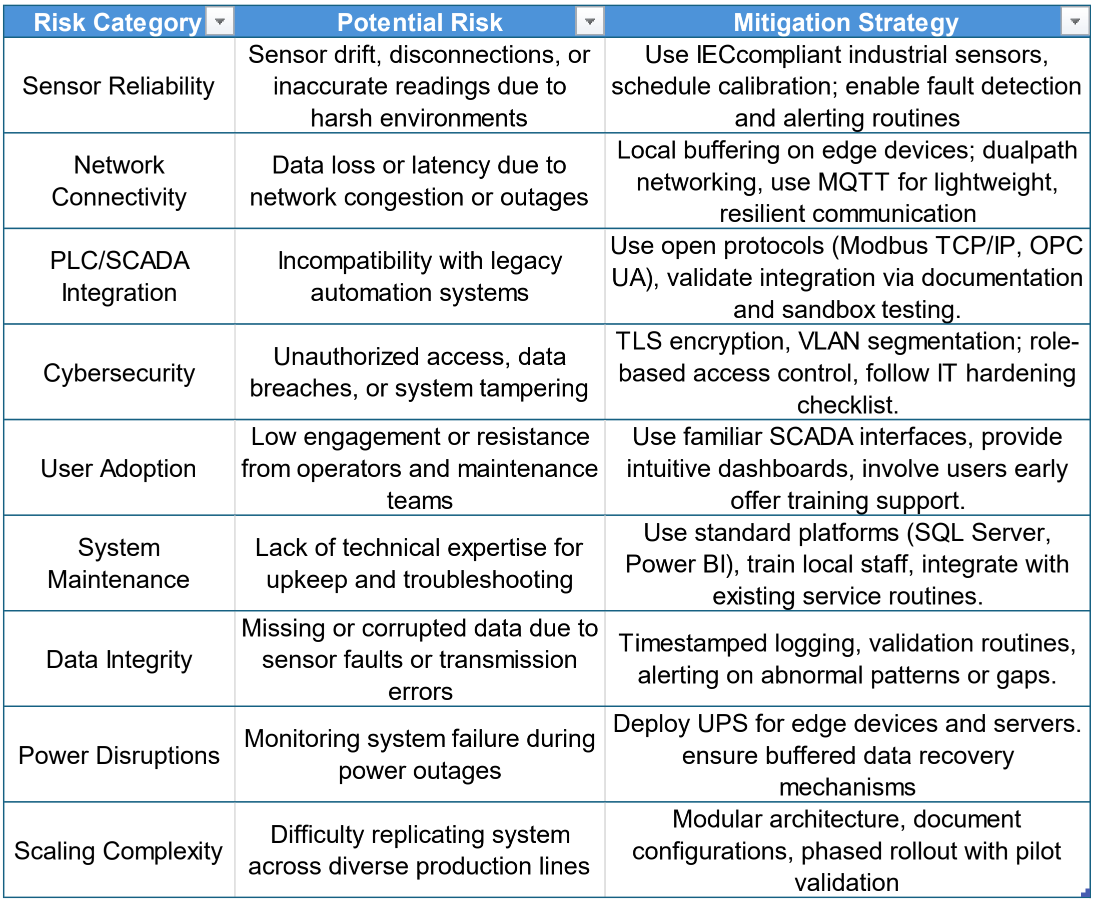
7.1 Overview

Deploying an IoT based energy monitoring system in a food and beverage production environment introduces a range of technical, operation, cybersecurity, financial and organisational risks. Although the system is designed to be non-intrusive and independent from existing process control, it still interacts with electrical infrastructure, industrial networks, servers, and factory personnel. Therefore, understanding these risks and establishing effective mitigation strategies is essential to ensure successful implementation and long-term reliability.

This section evaluates all major risk categories, including technical failures, data quality issues operator adoption challenges, cyber security issues, integrations obstacles and long-term sustainability. The analysis is based on best practices, comparable IoT deployments and practical knowledge of Tetra Pak production environments.

7.2 Identified Risks and Mitigation strategies

Figure 12 presents a risk management framework for IoT and SCADA implementation in industrial environments. The table outlines key risk categories such as sensor reliability, network connectivity, PLC/SCADA integration, cybersecurity, user adoption, system maintenance, data integrity, power disruptions, and scaling complexity. For each category, potential risks are identified along with corresponding mitigation strategies, including industrial sensor calibration, local buffering, use of open protocols, TLS encryption, operator training, and modular architecture for scalability.



Risk Category	Potential Risk	Mitigation Strategy
Sensor Reliability	Sensor drift, disconnections, or inaccurate readings due to harsh environments	Use IECcompliant industrial sensors, schedule calibration; enable fault detection and alerting routines
Network Connectivity	Data loss or latency due to network congestion or outages	Local buffering on edge devices; dualpath networking, use MQTT for lightweight, resilient communication
PLC/SCADA Integration	Incompatibility with legacy automation systems	Use open protocols (Modbus TCP/IP, OPC UA), validate integration via documentation and sandbox testing.
Cybersecurity	Unauthorized access, data breaches, or system tampering	TLS encryption, VLAN segmentation; role-based access control, follow IT hardening checklist.
User Adoption	Low engagement or resistance from operators and maintenance teams	Use familiar SCADA interfaces, provide intuitive dashboards, involve users early offer training support.
System Maintenance	Lack of technical expertise for upkeep and troubleshooting	Use standard platforms (SQL Server, Power BI), train local staff, integrate with existing service routines.
Data Integrity	Missing or corrupted data due to sensor faults or transmission errors	Timestamped logging, validation routines, alerting on abnormal patterns or gaps.
Power Disruptions	Monitoring system failure during power outages	Deploy UPS for edge devices and servers. ensure buffered data recovery mechanisms
Scaling Complexity	Difficulty replicating system across diverse production lines	Modular architecture, document configurations, phased rollout with pilot validation

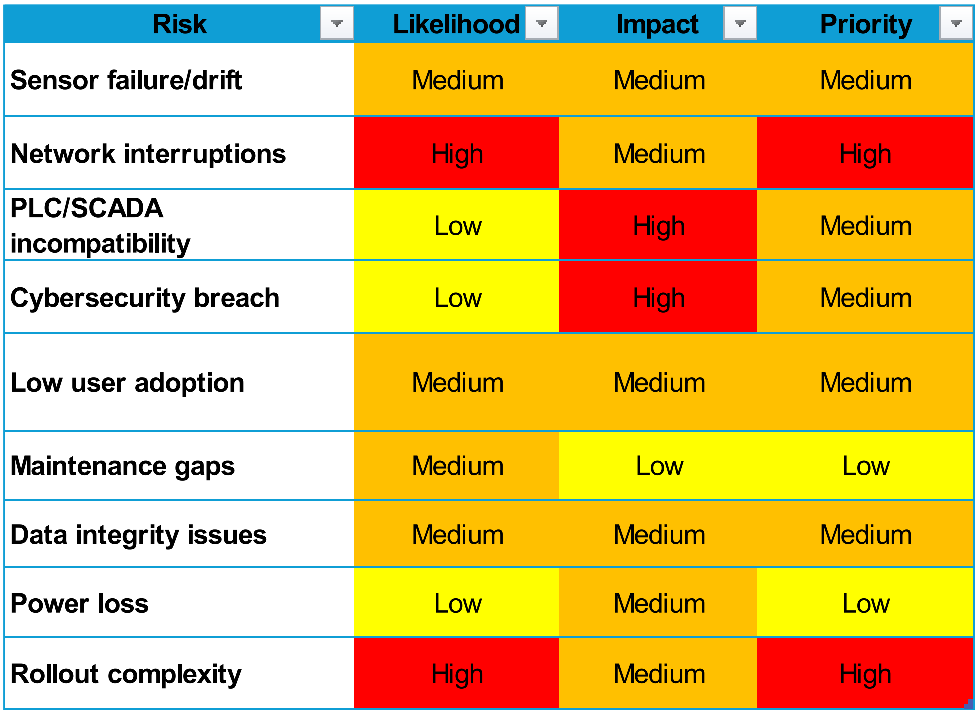
Figure.12. Risk management framework for IoT and SCADA implementation in industrial environments.

7.3 Risk prioritization

The following table shows my assessment of nine key risks in the IoT energy monitoring rollout. I used a risk matrix to evaluate each risk based on its likelihood of occurrence and potential impact. For example, network interruptions are highly likely and moderately impactful, making them a high-priority concern. In contrast power loss is unlikely and only moderately impactful so it is classified as a low priority. This approach enables me to allocate resources efficiently and focus on risks that could most significantly disrupt operations.

Figure 13 illustrates the risk analysis matrix for the proposed IoT energy monitoring system. It categorizes risks such as sensor failure, network interruptions, PLC/SCADA incompatibility, cybersecurity breaches, low user adoption, maintenance gaps, data integrity issues, power loss, and rollout complexity. Each risk is color-coded by likelihood, impact, and overall priority, providing a clear visual representation of where mitigation efforts should be concentrated.

General



Risk	Likelihood	Impact	Priority
Sensor failure/drift	Medium	Medium	Medium
Network interruptions	High	Medium	High
PLC/SCADA incompatibility	Low	High	Medium
Cybersecurity breach	Low	High	Medium
Low user adoption	Medium	Medium	Medium
Maintenance gaps	Medium	Low	Low
Data integrity issues	Medium	Medium	Medium
Power loss	Low	Medium	Low
Rollout complexity	High	Medium	High

Figure.13. Risk analysis matrix for the proposed IoT energy monitoring system (source: authors creation).

7.4 Risk management summary

The system introduces several risks typical of connected industrial environments, all identified issues can be managed through engineering and IT best practices. The use of industrial grade hardware, open protocols, modular design, and secure deployment practices significantly reduces exposure to critical failures. Addressing risks during the planning, pilot and training phases, guaranteeing a controlled implementation, and minimising operational disruptions throughout.

8 LEGAL AND ENVIROMENTAL CONSIDERATIONS

8.1 Overview

Legal and environmental feasibility examines the compliance, regulatory, sustainability and environmental impact aspects of implementing the IoT based energy monitoring system. For food beverage manufacturers, many of whom operate within tightly regulated environments, legal compliance and environmental responsibility are fundamental requirements. Tetra Pak as both supplier and global leader in sustainable production systems must ensure that any proposed monitoring solution aligns with international standards, local regulations, cybersecurity directives, and environmental management framework.

This section evaluates the legal, regulatory, cyber security, data protection and environmental considerations associated with deploying the system. It demonstrates that the proposed solution aligns closely with Tetra Paks corporate sustainability strategy and supports customers in achieving their own sustainability and compliance objectives.

8.2 Legal compliance and data protection

Although the proposed system does not process personal data, it operates within a broader IT/OT ecosystem where access to machine logs, production metrics and networked devices may involve sensitive operational data. Legal and regulatory considerations include (European Union, 2018 European Union, 2023 International Electrotechnical Commission, 2018):

GDPR (General Data Protection Regulation) while focused on personal data, GDPR principles such as data minimization and secure access apply to user credentials, audit logs, and remote diagnostics. Role based dashboards must ensure proper authentication and traceability.

NIS2 Directive (EU) Applicable to critical infrastructure sectors including food and beverage manufacturing. If the system affects operational continuity or data availability it must meet minimum cybersecurity standards, including incident reporting and access control.

Internal IT Policy Compliance: All components must adhere to Tetra Pak IT governance, including network zoning approved software stacks and audit readiness.

Safeguards implemented:

- TLS encryption for MQTT and HTTP based data transmission.
- Role based access control and password-protected dashboards.
- Secure data storage on SQL server or approved cloud environments.
- Full logging of system changes, user access, and data exports.

These measures ensure the system can be deployed securely and in compliance with both external regulations and internal IT policies.

8.3 Environmental impact

The system is designed to reduce environmental footprint of industrial operations by enabling granular and real time visibility into energy and utility consumption. Major key environmental benefits include reduced CO2 emissions and energy waste through early detection of inefficient operating conditions such as idle loads, poorly tuned heating profiles, and excessive compressor usage. Optimized CIP (Cleaning in place) cycles by monitoring water, chemical, and energy usage during cleaning processes reducing waste while maintaining hygiene standards necessary in the food and beverage industry.

Minimize water and thermal losses, especially in pasteurization and cooling processes, which are major contributors to utility load.

Lower material waste and product loss through fault detection and predictive diagnostics reducing line stops and deviations.

These outcomes support Tetra Paks sustainability roadmap and enhance environmental, social, governance reporting capabilities.

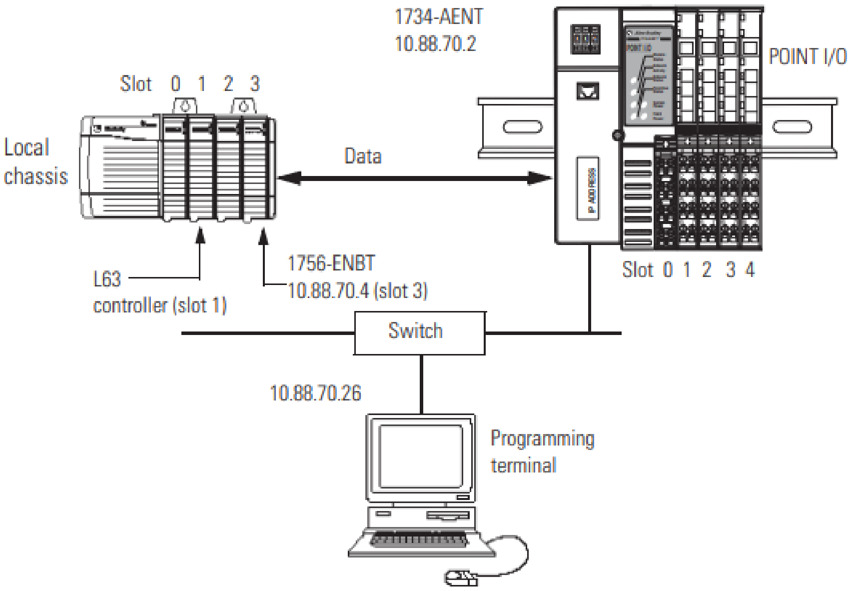


Figure.14. Ethernet/IP network architecture with controller, ENBT module, and I/O adapter (adapted from Rockwell Automation literature).

8.4 Alignment with standards certifications.

The IoT system is to be designed to align with key international standards and certifications. Aligning with ISO standards not only ensures compliance but also reinforces Tetra Paks reputation as a sustainability leader.

- ISO 50001-Energy Management Systems, which supports continuous improvement of energy performance through machine-level monitoring and analytics.
- ISO 14001 -Environmental Management Systems, enabling real time tracking of environmental KPIs supporting compliance and sustainability initiatives.

- IEC 62443- Industrial Cybersecurity: While not mandatory, adherence to its principles (e.g. defence in depth, secure communications) enhances system resilience.
- Corporate ESG Programs the system supports Tetra Paks environmental commitments by enabling transparent reporting on energy use, emissions, and resource efficiency.
- EU Green Deal & Fit for five reducing energy waste, the system contributes to industrial decarbonization and aligns with European climate targets.

This alignment ensures smoother audits, improved stakeholder trust, and strategic readiness for evolving regulatory landscapes.

8.5 Regional and National Regulations.

Energy monitoring also intersects with regional and national regulations. Depending on plant location, operators may be obligated to meet requirements such as:

- EU Energy Efficiency Directive (EED).

Require large companies to conduct regular energy audits and demonstrate improvements.

Machine-level visibility simplifies compliance and improves audit accuracy.

- EU NIS2 Directive (2023).

Mandates stronger cybersecurity measures for critical infrastructure and manufacturing sectors.

The system complies through secure communication, network segmentation, and role-based access control.

- Local environmental reporting laws.

Many countries require reporting on energy use, emissions, water consumption, and waste generation.

Machine-level energy data supports detailed and verifiable reporting.

- National Electrical Safety Codes.

Sensors and gateways must meet national electrical standards such as CE, UL, CSA, or similar certifications.

Because the system is non-intrusive and uses certified industrial hardware, compliance with these requirements is straightforward.

8.6 Alignment with the company’s sustainability strategy

Tetra Pak has committed to ambitious sustainability targets including reductions in greenhouse gas emissions, increased use of renewable electricity and support for economy principles. The introduction of a machine level energy monitoring system aligns directly with the goals:

- Providing data required for energy efficiency improvements.
- Supports reductions in CO2 emissions across the value chain.
- Enabling production facilities to track environmental performance accurately.
- Reducing waste associated with overproduction or inefficient equipment operation.

The system strengthens Tetra Paks environmental value proposition to customers.

8.7 Summary

The proposed monitoring system is legally and environmentally feasible across major markets where Tetra Pak operates. Strengthening compliance with energy, environmental and cyber security regulations whilst supporting sustainable production practices and industry standards such as ISO 50001, ISO 14001, and IEC 62443. The system introduces no legal barriers, requiring minimal personal data handling and integrates smoothly into existing governance frameworks.

Environmentally the solution delivers clear and measurable benefits, enabling reductions in energy waste. Emissions, water use, and utility inefficiencies. These enhancements contribute to Tetra Paks long term sustainability goals while helping customers meet regulatory and corporate performance requirements.

Over legal and environmental feasibility Is strong reinforcing the case to implement pilot installations scaling the system across customer sites.

Figure 15 shows an Allen Bradley CompactLogix controller used for testing, which could serve as the gateway for the proposed IoT energy monitoring system. This hardware demonstrates compatibility with industrial automation standards and supports integration with edge computing and SCADA environments.

Figure.15. An Allen Bradley CompactLogix used for testing, which could be the gateway for the proposed IoT energy monitoring system (source: author’s own photo).

9 CONCLUSION

9.1

This feasibility study sets out to evaluate the design, deployment potential, and operational impact of an IoT based energy monitoring system tailored to Tetra Pak and its customers processing and filling equipment. The motivation behind this project stems from the growing demand for improved energy efficiency, sustainability, and operational transparency in the food and beverage industry where energy intensive processes such as heating, cooling, and cleaning are central to production.

The study confirms technical, economic, and operational feasibility and more importantly demonstrates how this solution can become a strategic differentiator for Tetra Pak in a market where energy efficiency is both cost and compliance imperative.

From a technical perspective, the study demonstrates that the system is fully feasible using existing industrial technologies, including non-intrusive sensors, reliable IoT gateways, standard communication protocols such as MQTT and OPC UA, and robust data storage platforms such as Microsoft SQL Server. The proposed architecture integrates seamlessly with Siemens, Rockwell, and Beckhoff automation systems without modifying validated PLC logic. This nonintrusive design ensures that process safety, quality and uptime are unaffected while enabling high-resolution data collection at machine level.

In terms of economics the system shows promising potential for return on investment, with projected energy savings of ten -20% this is based on industry benchmarks. The initial implementation cost is low particularly when starting with a pilot deployment and ongoing maintenance costs are minimized through the reuse of existing infrastructure such as SCADA terminals and remote service computers. This makes the solution both scalable and cost effective.

Operational feasibility is equally strong. The system requires minimal training, integrates with existing dashboards and workflows, and enhances rather than disrupts daily routines for operators, maintenance personnel, and energy managers. Because the solution is red only and operates independently of process control systems, it poses no risk to food safety, production continuity, or equipment performance. Its maintainability is supported by industrial grade hardware, low service requirements, and software tools that are already familiar to plant personnel.

Instead of constructing a physical prototype this feasibility study was developed, as a validation approach based on technical insights, documentation revies and on-site assessment. This method ensures that the proposed IoT energy monitoring system can be implemented barely interrupt operations, being strongly compatible with existing infrastructure common across Tetra production facilities and a cost that remains reasonable for stakeholders and customers.

Additionally, the system’s ability to monitor auxiliary utilities including steam, water, cooling energy alongside electrical consumption enhances its value. Supporting multi utility tracking the system enables more accurate calculation of Specific Energy Consumption (SEC) and provides deeper insights into energy intensity across various production modes, including cleaning in place processes. This broad scope supports targeted energy optimization strategies and aligns with sustainability goals.

Overall, the feasibility study concludes that an IoT based energy monitoring system is not only technically achievable but also economically advantageous, operationally practical, legally compliant, and environmentally beneficial. Implementing such a system would provide Tetra Pak and its customers with meaningful insights into energy consumption, improve resource efficiency, supports regulatory compliance as well as strengthening long-term sustainability performance. A phased approach beginning with pilot installation followed by gradual scaling across equipment and production lines is recommended as the most effective path toward full deployment.

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APPENDIX 1: LIST OF ABBREVIATIONS

AI – Artificial Intelligence
CIP – Cleaning-in-Place
CO_2 – Carbon Dioxide
ERP – Enterprise Resource Planning
GDPR – General Data Protection Regulation
HMI – Human-Machine Interface
HTTP – Hypertext Transfer Protocol
IEC – International Electrotechnical Commission
IEA – International Energy Agency
IIoT – Industrial Internet of Things
IoT – Internet of Things
I/O – Input/Output
IP – Internet Protocol
ISO – International Organization for Standardization
IT – Information Technology
KPI – Key Performance Indicator

MES – Manufacturing Execution System

MQTT – Message Queuing Telemetry Transport

NIS2 – EU Directive on Network and Information Security (v2)

OPC UA – Open Platform Communications Unified Architecture

PC – Personal Computer

PLC – Programmable Logic Controller

ROI – Return on Investment

SCADA – Supervisory Control and Data Acquisition

SEC – Specific Energy Consumption

SQL – Structured Query Language

TCP/IP – Transmission Control Protocol / Internet Protocol

TLS – Transport Layer Security

UPS – Uninterruptible Power Supply

VPN – Virtual Private Network