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Sustainable Manufacturing in Industry 4.0: Enhancing Safety and Rapid Response in Industrial Control Systems with Smart Edge IoT Devices

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Abstract:- In This research, we delve into the dynamic synergy between sustainable energy and Industry 4.0 within the field of "Energy and Sustainable Engineering." It centers on integrating an emergency email generation system into a robust digitalization framework. The study prioritizes hands-on training, emphasizing practical applications that blend sustainable energy practices with the transformative principles of Industry 4.0. By focusing primarily on the intersection of sustainable energy, the project underscores the crucial role of digitization. This seamless integration aligns with the principles of automation, smart technologies, and the evolving landscape of digitization within industries committed to sustainable energy practices. The primary objective in this experiment is to integrate Industrial IoT into the realm of smart manufacturing, effectively incorporating our system into the framework of Industry 4.0, while prioritizing energy sustainability. Through this integration, our experimental results demonstrate that in the event of an emergency condition, instead of the automation system persisting under faulty conditions, an email notification is immediately sent to the operator, facilitated by IoT. This approach not only ensures swift response to critical situations but also contributes to energy conservation and overall sustainability. This initiative significantly contributes to ongoing discussions surrounding sustainable energy, digital transformation, and Industry 4.0, marking a significant step forward in promoting conscientious industrial practices for the future.

Keywords:- *Industry 4.0, Sustainable Energy, Digitization, Industrial Internet of Things.*

I. INTRODUCTION

In recent years, industrial production has undergone a profound shift, known as 'Industry 4.0.' This transformation involves heightened digitalization, leading to intelligent, connected, and decentralized production systems. Industry 4.0 aims to deeply integrate emerging technologies into business and engineering processes, fostering flexible, efficient, and sustainable production with a focus on maintaining high quality and minimizing costs [1]. Industry 4.0, also known as the fourth industrial revolution, involves interconnected and embedded systems that blur the lines between physical and virtual factories, all made possible through the implementation of the Internet of Things [2]. The ongoing Fourth Industrial Revolution, is reshaping global industries through the integration of transformative technologies like Augmented and Virtual Reality, Industrial Internet of Things, Artificial Intelligence, and Big Data. The digital metamorphosis instigated by Industry 4.0 not only revolutionizes manufacturing efficiency but also holds the key to significant advancements in energy sustainability [3]. The essence of Industry 4.0 lies in its digital connectivity and information sharing, offering a powerful but potentially contradictory impact on triple bottom line sustainability economic, environmental, and social. The digitization of manufacturing processes and the integration of smarter machines can yield advantages like increased productivity, enhanced resource efficiency, and reduced waste. Looking through the lens of social development, it is believed that this digital shift will create a multitude of job opportunities in specialized areas like automation engineering, control system design, machine learning, and software engineering [4].

The Industrial Internet of Things (IIoT) represents an advanced segment within the broader Internet of Things (IoT). It intricately intertwines networked devices and state-of-the-art technologies, specifically tailored for seamless integration with automation applications designed for industrial communication. [7]. The Industrial Internet of Things (IIoT) enables the integration of computer automated control systems, facilitating remote monitoring and swift response to real-time events. In the past, facilities managers faced delays in physically attending to control systems, often leading to damages. In the IoT era, control commands can be instantly issued from devices like PCs, tablets, or cellphones to any location within a facility. This immediate response capability can prevent costly damages and potential disasters, saving both the company and the environment. Modern control system gateways, equipped with substantial computational power and increased storage/memory space, along with enhanced security features in client devices, are now adept at managing remote access security requirements. The utilization of cloud services in conjunction with control system gateways has become a prevalent approach. This dual-option strategy expands the capabilities of control systems and automation, introducing new possibilities and challenges in the process [5].

II. LITERATURE REVIEW

The literature review for the research focus on enhancing the security of industrial control systems, particularly in the context of Industry 4.0 and the Industrial Internet of Things (IIoT). Tan Ching Ng et al. [3] proposed seven Industry 4.0 energy sustainability functions, including improved methods of production, energy sector transformation, improved production management, informed decision making, new business models, smart energy management systems, and value chain digitization. Guo-jian Cheng et al. [8] contributed to the field as it discusses the core concept of Cyber Physical system (CPS), which integrates computing, communication, and control to achieve collaborative and real-time interaction between the real world and the information world. Industry 4.0 Development and Application of Intelligent Manufacturing. Michal Wisniewski et al. [6] concentrated on the multifaceted realm of safety within Industry 4.0 (I4.0), encompassing diverse elements, systems, and processes. Instead of delving into narrower, more technical security concerns, the authors opt for a broader categorization into three levels: process, data, and infrastructure, alluding to the potential application of different technologies to augment the security, transparency, and traceability of I4.0 solutions and systems. Additionally, Martin Wollschlaeger et al. [11] explores the evolution and impact of industrial communication systems in the context of automation networks, considering the rise of the Internet of Things (IoT) in industrial applications. It emphasizes the technological trends, including Ethernet time-sensitive networking (TSN) and the role of fifth-generation (5G) telecom networks in industrial automation. The historical background of industrial communication networks is detailed, highlighting the development of fieldbus systems, Ethernet-based networks, and wireless networks. Michael W.Condry et al. [5] focused into the security challenges arising from the integration of Industrial Internet of Things (IoT) devices and control system gateways in Internet-connected control systems. It emphasizes the vulnerabilities associated with single-factor authentication and proposes a robust solution in the form of Multifactor Authentication (MFA), incorporating elements such as usernames, passwords, tokens, and biometrics. Real-Time Identity Monitoring is introduced as an additional layer of security to continuously verify the user's identity, detect potential anomalies, and ensure secure operations. The proposed security model establishes a trusted state between IoT client devices and control system gateways. Shrouf [12] By understanding production processes and energy consumption behaviors, companies can optimize production schedules and machine configurations to minimize energy usage. This holistic approach to energy management ensures that energy efficiency is integrated into production planning practices. Cioffi, R [13] proposed IoT-connected devices can facilitate demand response strategies by adjusting energy consumption based on peak/off-peak hours or grid conditions. This flexibility helps in reducing overall energy demand and supporting grid stability. By collecting and analyzing vast amounts of data from IoT devices, smart manufacturing systems enable data-driven decision-making for energy management. Companies can identify patterns, trends, and opportunities to enhance energy sustainability practices. Matsunaga, F[14] Digital Twin (DT): A digital representation of a physical system that can be used to analyze and optimize energy consumption. IIoT Connects machines and devices in industries for improved data exchange and operational efficiency, contributing to energy savings. Onu [15] The challenges in implementing these technologies, such as the need for standardization and addressing cybersecurity risks, while pointing out the opportunities they present for creating a more sustainable energy future. These technologies are pivotal in transitioning towards a cleaner, more efficient, and sustainable energy system.

III. METHODOLOGY

In the ever-evolving landscape of contemporary industrial processes, the infusion of digital technologies has transitioned from being optional to imperative, particularly in the context of advancing sustainable energy practices within Industry 4.0. The intricate dynamics of the system emanate from external influences such as inputs and disturbances, generating a multitude of outputs within its environmental context. Furthermore, internal failures within the P3 system components introduce an additional layer of complexity, occasionally leading to 'self-interactions' within the three major categories of system components. Augmenting this complexity are the interactions and interfaces among the plant, individuals, procedures, and the reciprocal relationships between them [9]. Industry 4.0's first major shift is driving advanced digitization. This, coupled with cutting-edge internet-based technologies like smart objects, paves the way for a future where factories become modular, highly efficient production systems. In this vision, products themselves take control of their own manufacturing process [10]. This research represents a dedicated effort to practically apply the principles of digitalization by integrating Programmable Logic Controller (PLC) logic with a Festo setup, with a primary focus on fostering sustainable energy solutions. The setup takes place against the backdrop of key components, each playing a pivotal role in the practical implementation of digitalization. These components include electropneumatic circuitry, mini control system configuration, communication network setup, OPC server establishment, and push notification configuration.

A. Step 1 – Establishing Sustainable Electropneumatic Circuit for Industry 4.0 Integration

In the inaugural phase, the primary emphasis is on configuring a comprehensive electropneumatic circuit designed to seamlessly integrate with Industry 4.0 principles, with a specific focus on promoting sustainable energy practices. This step involves not only establishing circuit connections but also providing a detailed overview of the selected components chosen for their compatibility with sustainable energy solutions.

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Table 1: Components used in Electro Pneumatic Setup

No.	Components	Quantity
1	Siemens Logo PLC	1
2	Flow Sensor SFAB-50U	1
3	5/2 Single solenoid valve	1
4	Pressure Regulator VPPE-3-1	1
5	Festo Inductive Sensor	1
6	Emergency Switch	1
7	Double Acting Cylinder	1
8	Flow Control Valve	2
9	Compressed Air pressure sensor (spau-p10r-w-g18fd-I-pnlk-pnvba-m8u)	1

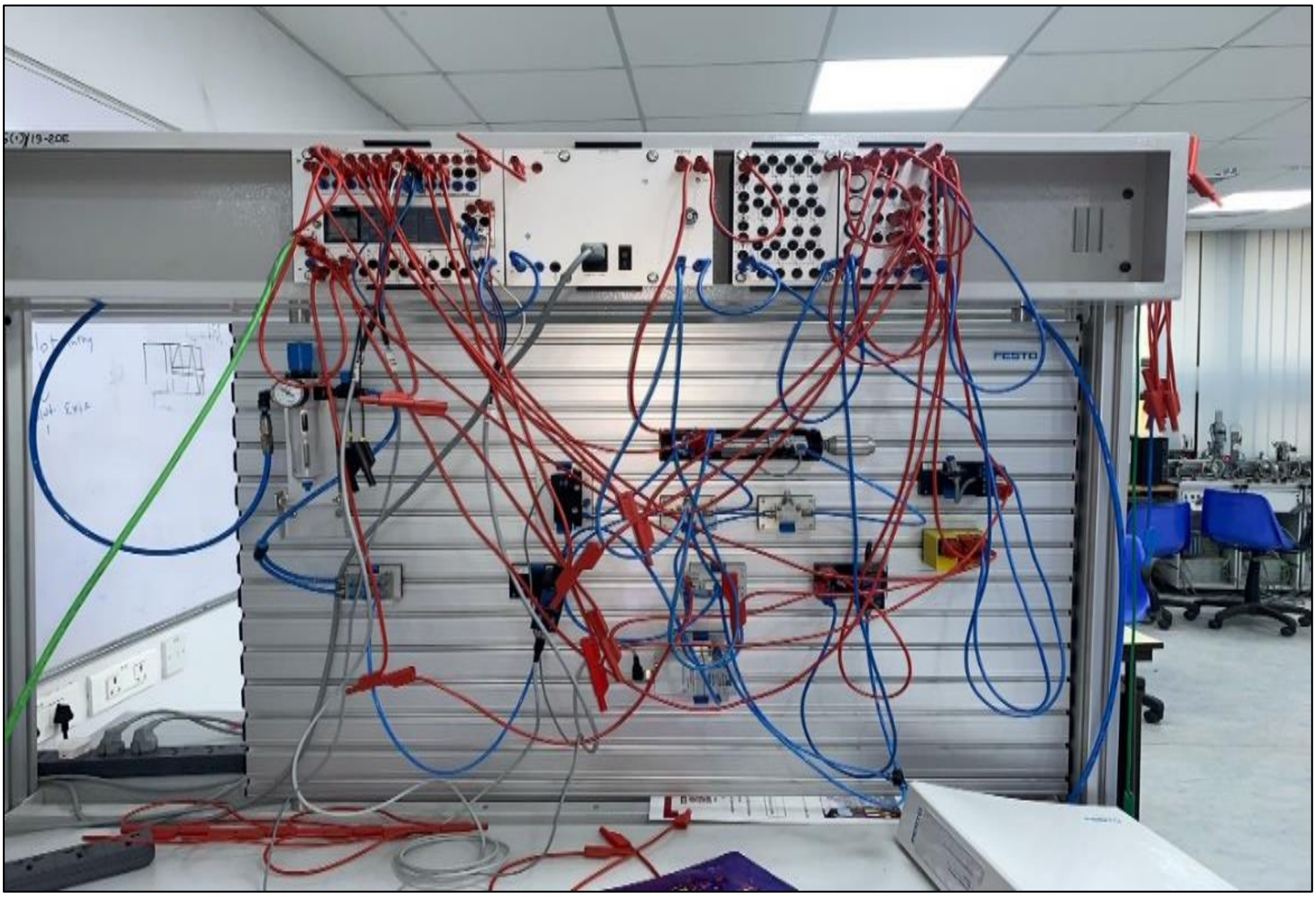

Fig 1: Industry 4.0 Experimental Setup

The integration of sustainable energy solutions within Industry 4.0, we meticulously set up pneumatic connections to facilitate the seamless operation of our system. In Fig. 1, Initiating the process, the pneumatic source is activated, and the ensuing pressure is carefully monitored using a flow sensor. Subsequently, the flow regulator is engaged to meticulously control and regulate the system's pressure. The pneumatic air is then directed through a sequence of components, including a 5/2 solenoid valve, a pressure valve, and finally to the inlet valve of the Double Acting Cylinder (DAC). The DAC undergoes extension until the piston reaches its fully extended position, at which point an inductive sensor signals the controller about the end position. In the retraction phase, the controller employs the second port of the 5/2 solenoid valve, facilitating the passage of exhaust air through the pressure valve and returning it to the second port of the 5/2 solenoid valve. Throughout this process, the compressed air pressure in the pressure regulator is continuously monitored using a compressed air pressure sensor. Control mechanisms, including an On and Off switch and an emergency stop switch, are integrated with the controller to provide overall system control, allowing the operator to halt the system immediately in the presence of perceived hazards. All components are intricately connected electrically to the Programmable Logic Controller (PLC), which assumes the responsibility of monitoring, controlling, and actuating each component based on programmed logic, thereby ensuring the sustainable and efficient use of energy in the Industry 4.0 automation sector.

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Fig. 2 represents the design of the flow of a program graphically. Here, If the system is in initial position le. there is no stop signal (emergency stop, STOP button, external stop) and the cylinder is retraced for a second, the sequence is started with the start button/self-latching loop The cylinder extends and the self-latching loop is set. The cylinder remains in pressing position for three seconds and then retracts. When the self-latching loop is set, it remains in initial position for a second and the cycle is restarted. Now, At any time, a stop signal will lead to the cylinder immediately retracting again, the self-latching loop will be reset and the acknowledgement light will go on. The acknowledgment button switches the acknowledgement light off again and the system will be at the initial step again, the start-up will be possible when the stop signal is no longer present.

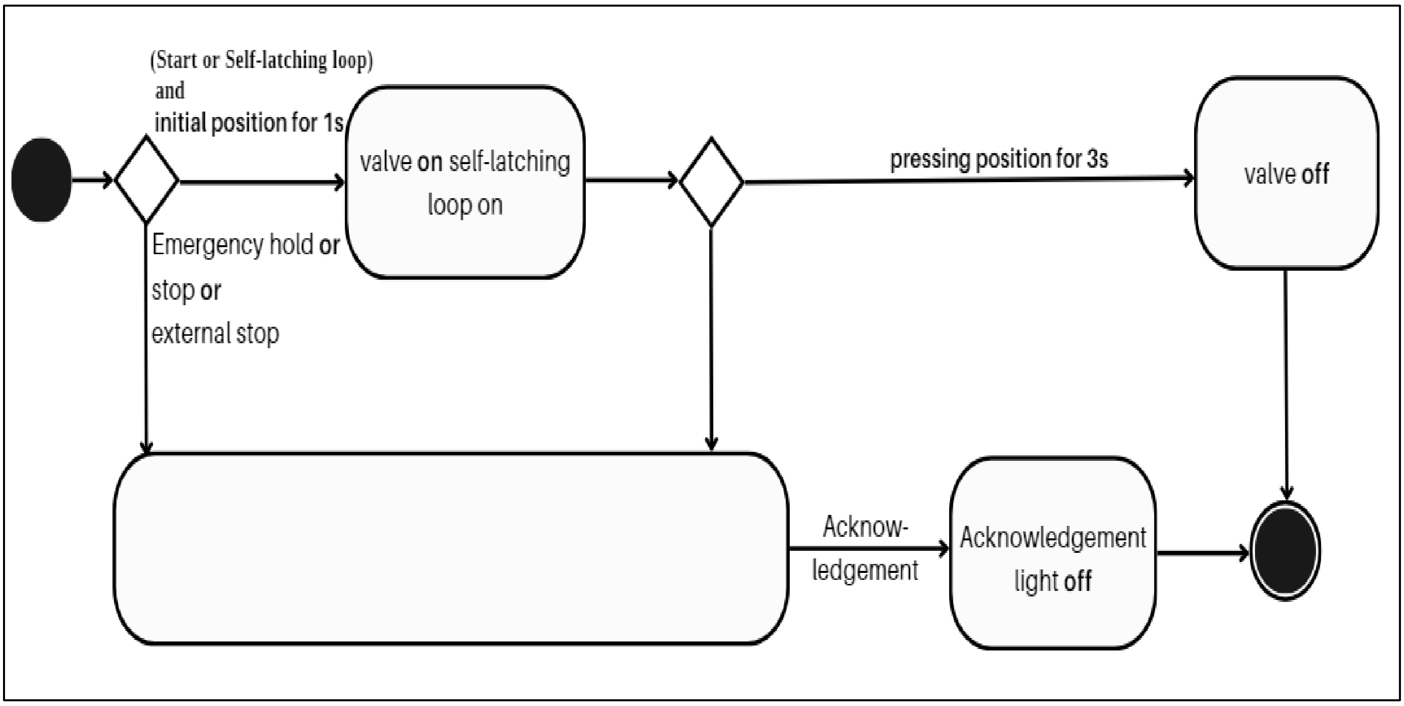

Fig 2: Program Flow of Experimental Setup

B. Step 2 – Establishing the Communication Network

This involves tailoring settings for the WLAN access point to establish a resilient network, assigning a static IP address for the LOGO! PLC to ensure stability, aligning the network architecture in accordance with the positional sketch, optimizing the configuration of the OPC server for streamlined data exchange, and initiating the commissioning process for the measuring software.

Table 2: Components Used in Communication Network Configuration

No.	Components/Software	Quantity
1	Dlink WiFi Modem	1
2	WiFi router	1
3	Ethernet Cables	1
4	Windows console	-
5	Internet Explorer	-
6	TP 260 Software	-
7	LOGO!Soft Comfort 8.1	-

Fig. 3 is a network setup, featuring a computer and various devices interconnected through a router via a network of cables. Routers function as facilitators, allowing multiple devices to share a common internet connection. Within this network, the computer is linked to the router through an Ethernet cable, specifically connected to the "WAN" port on the router, designed for internet connectivity. The diagram illustrates a computer labeled as "PC." The connection to the router is established through a cable, strategically inserted into the "WAN" port, enabling the router's connection to the broader internet. Conversely, the diagram showcases diverse devices such as smartphones, tablets, seamlessly linked to the router through wireless connectivity. Each device is assigned a unique IP address, serving as a distinctive identifier within the network.

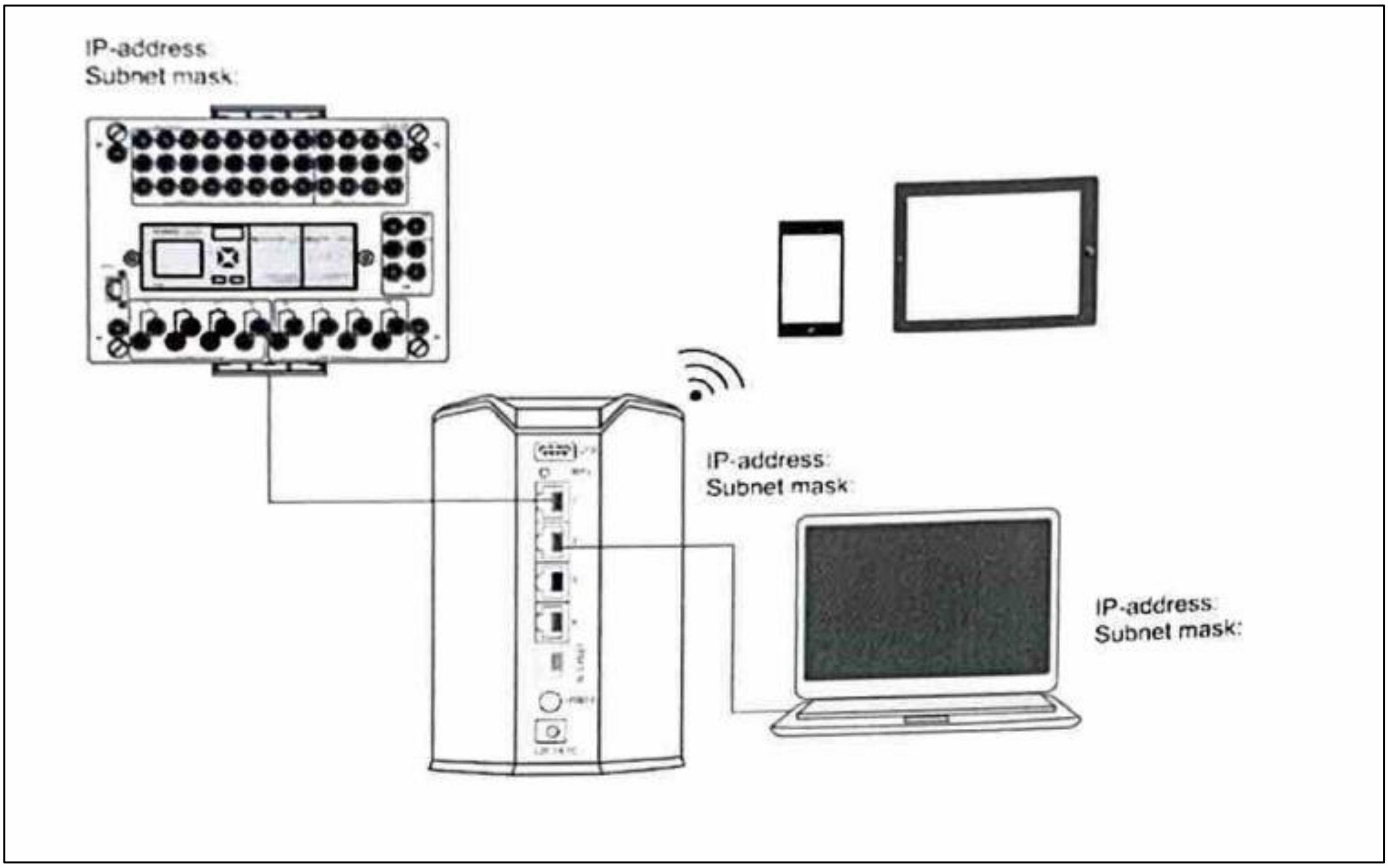

Fig 3: Positional Sketch of Communication Network Setup

The communication network serves as the digital backbone, facilitating the exchange of vital information between key components such as the LOGO PLC, main computer, and various interconnected devices. The network configuration encompasses both wired and wireless connections, optimizing the synergy between diverse elements within our setup. To elucidate the intricacies of this network, a comprehensive procedural flow has been devised and is visually represented in a detailed flowchart in Fig. 4.

Fig. 4 Communication Network Configuration Flowchart

IV. RESULTS

The result includes a compelling demonstration featuring a Gmail notification received during an emergency scenario, vividly showcasing the real-time communication capabilities integrated into our system. Swiftly generated upon detecting significant variations in critical parameters such as pressure or cycle time, the email notification underscores the system's prowess in identifying and promptly addressing emergent situations. The operator panel in Fig. 5 visually portrays monitored errors, encompassing issues like invalid pressure, invalid cycle time, and emergency stops. This graphical representation provides operators with immediate insights into the system's health, enabling swift responses to potential concerns. In Fig. 6, it showcases the Gmail notification received upon triggering an emergency scenario. Fig. 7 illustrating an email triggered for an invalid cycle time. The email notification is generated promptly when critical parameters such as pressure or cycle time undergo changes, signaling the system's adeptness in detecting and responding to emergent situations. This visual representation underscores the practical implementation and reliability of our sustainable energy and Industry 4.0 framework, providing a firsthand glimpse into the seamless and immediate alert mechanism employed by our system.

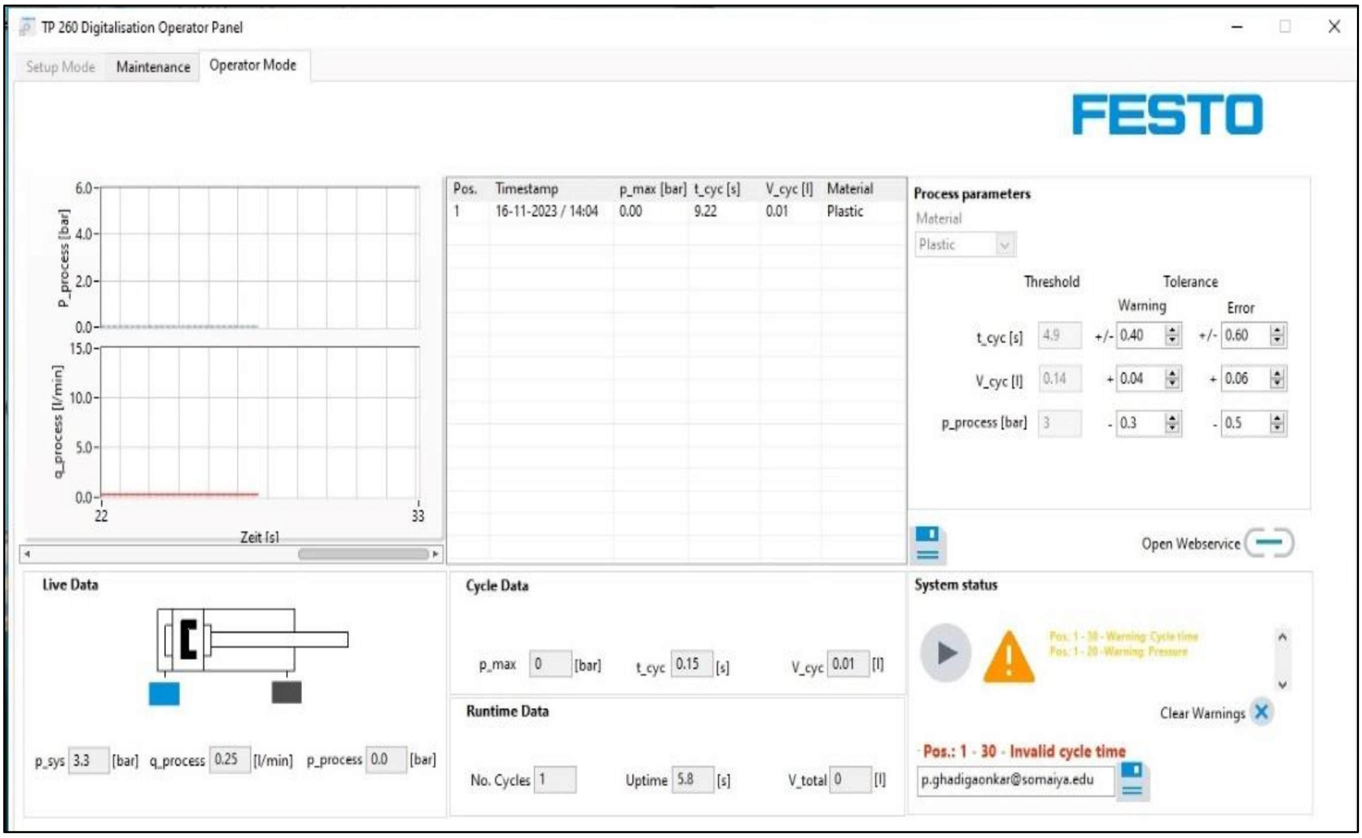

Fig 5: TP260 Operator Panel

Fig 6: Emergency Email Alerting Emergency Stop

Fig 7: Emergency Email Alerting Invalid Cycle Time

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V. CONCLUSION

The IoT experimental project has demonstrated significant contributions to both energy sustainability and the evolution of Industry 4.0. Through effective integration of IoT technologies, we addressed challenges in industrial energy consumption and efficiency, optimizing usage and contributing to cost savings and environmental sustainability. Additionally, experiment results have achieved notable success in enhancing operational resilience through the implementation of an automated email generation system during system failures or emergency scenarios. Triggered by the activation of an emergency button, this responsive mechanism ensures swift and targeted communication, providing real-time updates to stakeholders and facilitating efficient resource deployment. This proactive approach not only aligns with our project's overarching goals but also contributes to the overall success of our IoT infrastructure, emphasizing the multifaceted benefits of our solution in building a more resilient and connected future.

FUTURE WORK

Our research lays the foundation for promising future developments at the intersection of sustainable energy and Industry 4.0. The successful integration of our emergency email generation system within the digitalization framework opens avenues for further exploration. Future endeavors could focus on fortifying the system's security with advanced protocols, integrating advanced sensors for a more comprehensive understanding of industrial processes, and incorporating machine learning algorithms to enhance predictive capabilities.

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