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ENERGY EFFICIENCY OPTIMIZATION IN IOT-ENABLED MANUFACTURING USING FUZZY ALGORITHMS

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Abstract

This review examines the integration of the Internet of Things (IoT) and fuzzy logic algorithms for improving energy efficiency in manufacturing systems. Rising energy costs, environmental concerns, and the need for sustainable industrial operations have increased interest in intelligent energy management approaches. IoT technologies enable real-time monitoring of machine performance, process conditions, and energy consumption through interconnected sensors and devices. However, the large volume of data generated in such environments is often uncertain, incomplete, or imprecise. Fuzzy logic algorithms provide a suitable solution by supporting flexible decision-making under uncertain conditions. The article discusses how the combination of IoT and fuzzy logic can optimize energy use, reduce waste, improve operational efficiency, and support predictive maintenance in manufacturing environments. It also highlights key implementation challenges, including data processing complexity, system integration, and the need for adaptive control strategies. In addition, the review outlines the major benefits of this approach, such as cost reduction, environmental sustainability, and improved production performance. Overall, the review shows that IoT-enabled manufacturing systems supported by fuzzy logic offer strong potential for intelligent and sustainable energy optimization in modern industrial settings.

*Keywords**: IoT, fuzzy logic, energy efficiency, manufacturing, real-time optimization, predictive maintenance, sustainability, machine learning.***

1.0 INTRODUCTION

Energy consumption has risen as one of the most important issues in many industries and more so in manufacturing due to the fact that energy also forms a significant percentage of operating costs. The process of industrialization and ever-growing demand for products are among the factors that contribute to aggravation of worldwide predicaments related to energy consumption in manufacturing. (IEA, 2025; UNIDO, 2024). Manufacturing is one of the most energy-consuming sectors and thus contributes to high manufacturing cost and large ecological footprints, as still being the most important energy consumer (Rejeb et al. (2023). As an inducement of scaled industrial process, energy use in manufacturing sector is anticipated to experience a boost, thereby further stretching global energy supplies (Li et al. 2024). Energy consumption into the sector is associated with various energy-intensive operations from heating/cooling to machine running and it consequently has cumulative effect on environment of the unit, as also highlighted by Saini et al. (2024).

Large power usage in industries has caused harmful environmental and economic effects. For example, high level consumption of energy has led to the generation of significant greenhouse gases that have been associated with climate change (IEA, 2025; IPCC, 2023. Safa et al. (2023) reported that there is a growing demand for reducing energy consumption in the manufacturing sector as global efforts intensify toward achieving sustainability targets and minimizing the adverse environmental impacts of industrial activities.In the economic sense, high energy consumption results in high operating costs for industrial firms that operate on emerging markets where the price of energy is subject to uncertainty (IEA, 2024; World Bank, 2025). These expenses reduce profits and the ability to be competitive internationally. Indeed, to make itself more energy efficient is not just a green imperative but economic survival. Energy efficiency is a cornerstone of sustainable manufacturing, and provides multiple benefits including lower operating costs, less carbon emissions, as well as responsible use of our resources (IEA, 2025; UNIDO, 2024). Efficient energy use enables manufacturers to reduce their environmental footprint and have a better edge in the competitive market environment. Energy efficiency in manufacturing is perceived to be one of the channels to achieve both broader sustainability targets, complying with international environmental policies and strengthening the industry's resilience against variations in energy costs (IEA, 2025; UNIDO, 2024). Therefore, the energy efficiency optimization is the key factor of business and economy in the manufacturing sector.

1.1 IoT in Manufacturing

IoT has transformed the manufacturing industry by enabling smarter operations and improving resource efficiency. In industrial environments, the Industrial Internet of Things (IIoT) supports real-time data collection, monitoring, and control. As IoT-enabled devices and systems become more widely deployed in manufacturing plants, they facilitate the automation of complex processes, the optimization of production schedules, and the enhancement of product quality. By integrating sensors, actuators, cloud computing, and analytics, manufacturers can monitor and manage operations with greater accuracy, leading to improved resource management and energy optimization (Farooq et al., 2023; NIST, 2022; UNIDO, 2021).

The introduction of IoT-enabled smart factories has ushered in a new era in managing manufacturing processes. According to Roberts and Ramasamy (2023), the integration of IoT in manufacturing production enables constant machine, energy usage, and environmental condition surveillance. This ability lets manufacturers detect inefficiencies and make real-time adjustments to optimize energy consumption throughout a product's entire lifecycle. This has been confirmed by Vijayakumar (2023). Additionally, IoT enables predictive maintenance, thereby reducing instances of downtime and preventing energy wastage caused by equipment failure. As Kareem & Rajesh (2025) have explained. In essence, IoT has turned the conventional manufacturing facilities into dynamic and adaptive systems that focus on energy efficiency. Such optimization of processes, controls, and resource efficiency by IoT rests on the power of collecting vast data and processes for actionable insights. According to Safa et al. (2023), continuous monitoring by IoT systems offers manufacturers real-time data about energy use and helps them identify situations of inefficiency to take remedial measures. For example, in energy management systems, IoT provides energy consumption data of each machine, which assists the manufacturer in identifying those processes that consume a lot of energy and finding ways of reducing wastage, as identified by Tumula et al. (2024). Such optimization enables significant cost savings for manufacturers while enhancing operational efficiency and responding positively to sustainability concerns without compromising on market demands and environmental regulations. This fact is reiterated by Alshammri (2025).

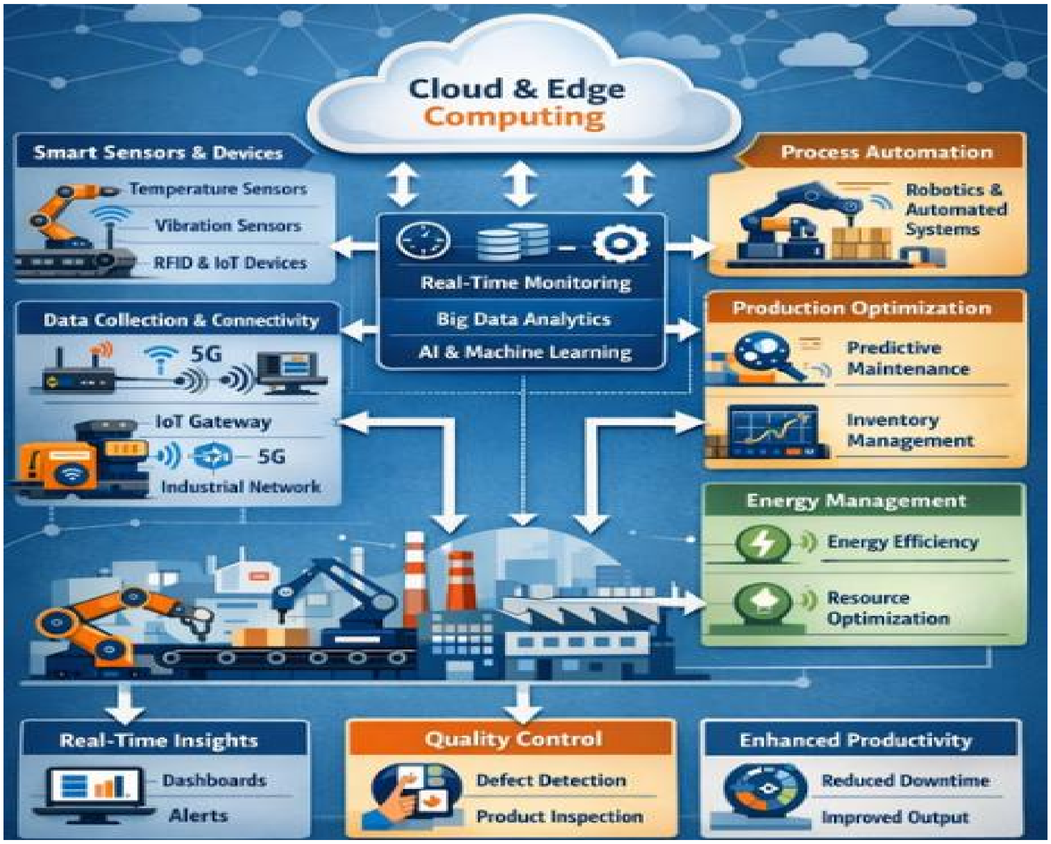

Figure 1: IOT in Manufacturing

1.2 Energy efficiency optimization challenges

Despite the significant potential of IoT for energy optimization, the manufacturing sector still faces several challenges in adopting effective energy management strategies. One of the most critical challenges is the inherent energy inefficiency of many industrial processes (IEA, 2025). According to Prakash et al. (2024), manufacturing processes currently depend on old equipment and inefficient energy systems that consume a huge amount of power. Moreover, industrial processes are usually complex with several stages, and each stage with a characteristic energy consumption which makes it significantly difficult to optimally minimize energy along the entire production chain (Jabeen et al., 2023). Adding to such inefficiency is that manufacturers cannot see energy use until it is too late to do anything to correct this. Further difficulties consist of the realtime energy management and optimization. Even though satisfactory advanced instrumentation and IOT technologies to monitor real time data acquisition are possible, processing of the data into useful intelligence is computationally intense and challenging (Krishnamoorthy et al., 2023). Sophisticated analytics and information processing tools and solutions are needed to make sense of the IoT data deluge. According to Gharaei & Alabdali (2025) real-time EMS should not only observe the energy consumption but also decide for sharing the energy in real time environments that are often unpredictable. Indeed, for many manufacturers the real-time processing of these systems and their ability to adapt to variations has become a particular problem (Khan et al., 2024).

The demand for such adaptive and intelligent systems in energy optimization is increasing as a static system becomes less responsive to changes in energy requirements. Such intelligence in these systems enables them to learn from the past data and hence can take the optimal decision for real-time adjustments in energy consumption (Jabeen et al., 2023). According to Tumula et al. (2024), such systems also need to incorporate intelligent algorithms able to cope with uncertainty and variability in energy consumption, particularly in complex manufacturing environments. Fuzzy logic control algorithms have been proposed as a promising alternative to this obstacle because they can cope with the uncertain nature of energy systems and thereby facilitate flexible and adaptive control strategies.

2.0 Methodology

2.1 Fuzzy Logic and Algorithms in Optimization

Fuzzy logic and a fuzzy system is a powerful energy efficiency optimization technique in IoT Based Manufacturing. The idea is basically based on their concept of “fuzziness,” that where data are imprecise or uncertain, it makes a decision by systems. Thus one may recommend that fuzzy algorithms be properly designed for optimization problems in the presence of incomplete and noisy data, something common in manufacturing. It will be possible to optimize efficiency without precise, deterministic information because manufacturers can make decisions in less rigid terms on the basis that fall short of relying on energy. Fuzzy algorithms were invented in the 60’s of last century, with groundbreaking contributions made by Lotfi Zadeh and his invention of fuzzy sets to model fuzziness. Since then, fuzzy logic has developed and been used in a lot of optimization algorithms like fuzzy-based control systems and methods for fuzzy clustering. Their application is even more relevant in case of complex non-linear systems, which should be considered when developing an energy optimization framework for the IoT-enabled manufacturing environment. Fuzzy systems can adapt to a dynamic environment, can handle large amounts of data and make decisions that would be impossible or very difficult with classical algorithms. It allows energy efficiency optimization for fuzzy algorithms in smart manufacturing of IoT, since the latter can process imprecision and uncertainty. Due to the enhanced complexity and data-driven nature in manufacturing practice, intelligent and adaptive systems are more desirable than ever before. On both FOG and EDGE nodes, fuzzy algorithms can process vast amount of realtime data from IoT devices more flexible and resilient with respect to energy optimization.

These systems are more than tools for improving energy efficiency, they serve a higher goal of sustainable manufacturing by guiding manufacturers to make decisions that best maximize the trade-off between operational performance and environmental concern**.**

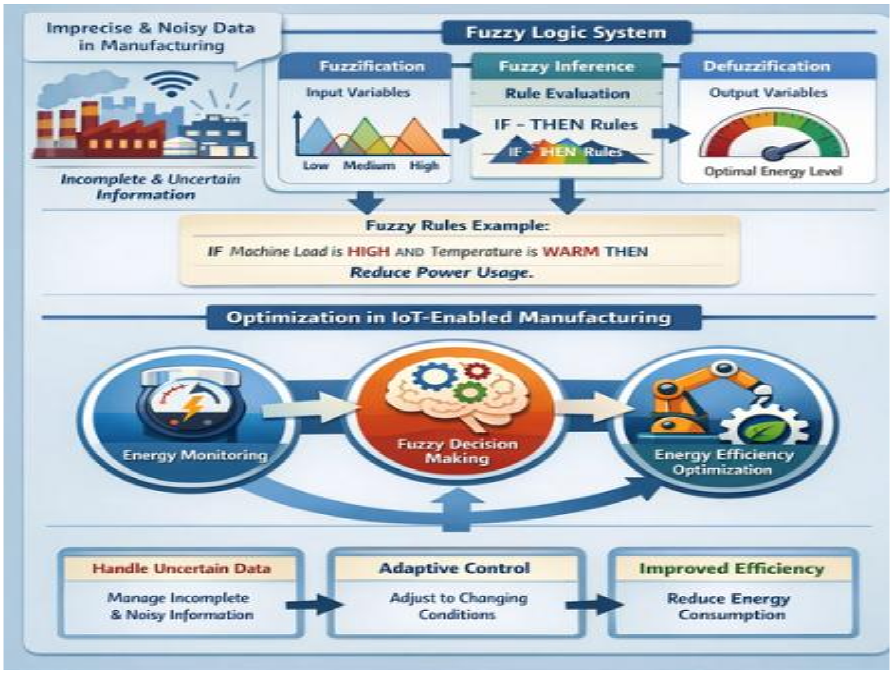

Figure 2: Fuzzy Logic and Algorithm in Optimization

2.2 Overview of IoT-Enabled Manufacturing

2.2.1 The Role of IoT in Manufacturing

IoT, the Internet of Things: A network between connected devices that can communicate and share information over the internet. According to usages, IoT solutions in the manufacturing industry are applied for monitoring, acquiring and controlling various processes or equipment in real-time. It involves the use of technology, integrated with sensors, actuators, communication technology and cloud-based analysis to monitor production processes for optimised manufacturing processes, enhanced quality control and high energy efficiency (Saini et al., 2024). Li et al. (2024) described in brief what IoT can contribute to the development of smart manufacturing plants were any machine, piece of equipment and even parts are connected to internet and their interaction supplies basic information that could be processed for improving decision making.

The difference-makers, essential for IoT in manufacturing are sensors that can detect information like temperature, humidity, vibration and power consumption; actuators to control machinery based on sensor signals; communication devices to transfer event data from sensors to control systems and software that analyses the incoming data from sensors while providing it with useful information (Gharaei & Alabdali, 2025). This IoT systems also aid in other manufacturing automatization and it enable manufacturers to monitor their processes from a far evaluate the current stock prediction maintenance (Safa et al., 2023).

For manufacturing, the effect of IoT has also been enormous in both efficiency and product quality. The top performing industry in adopting IoT has been of predictive maintenance where the equipment failure is anticipated by IOT sensors before happening and it allows the manufacturer to do maintenance only when needed rather than on defined intervals (Kareem & Rajesh, 2025). Sensor communication in manufacturing is further intended to optimize production lines by providing timely (real-time) information that can be used to adjust the manufacturing dynamically and with manageable waste, at least at optimisation wish level (Rejeb et al. ,2023). Automation: another pertinent application of IoT is in the manufacturing sector where it also helps ensure efficient control of manufacturing machines and system scarce interference by human labor factor, which significantly brings more efficiency, accuracy and speed without room for defect or error (Krishnamoorthy et al., 2023).

2.2.2 Smart Manufacturing and Industry 4.0

“IoT’s role in Smart Manufacturing and the so-called meaning of “Industry 4.0” refer to the Fourth Industrial Revolution which centers on digitalization, automation and data exchange among manufacturing technologies44) (Vijayakumar,2023). Weerawarana IoT in manufacturing helps to maintain connectivity, which allows everything including people and devices to interact with each other. According to Rajalingam et al. (2024), IoT in the context of industry 4.0 contributes to Cyber-Physical Systems (CPS) creation. Cyber-physical systems (CPSs) are mechanical, electronics and software components used for monitoring and controlling the physical world with computers. The IoT based devices implemented in the manufacturing helps to build a network of smart device and have tendency to perform multiple tasks such as watching, controlling and enhance the process (Kumar et al. 2023). This system is able to process data in real time and therefore increases efficiency of production (Jabeen et al. 2023). Furthermore, with the use of IoT devices in manufacturing manufacturers also could offer customer centric productions based on market trend which requires personalized items (Sikarwar & Tomar 2023). The impact of IoT on manufacturing efficiency and sustainability is pretty astonishing. Automation with the IoT in place As per Roberts & Ramasamy (2023), the automation that is resulting because of the existence of Internet-Of-Things, it so helps an organizations to override limitations that are faced by human capabilities, which in turn avoids errors, make processes efficient and brings much high returns for productivity. Further, using IoT organisations are able to monitor entire process of production and this in turn help the organisation to address inefficiencies, reduce wastage and make efficient use of energy too that also contribute towards sustainability (Li et al., 2024). Scope for IoT in enabling the organization reduce the adverse impact of business processes to mother nature is at par with sustainability (Saini, 2024).

2.2.3 Lookup Table-Based Proportional Controller for IoT

Energy usage is one of the most critical sectors where IoT adds value in the field of manufacturing. IoT sensors and smart energy meters help manufacturers monitor and control energy usage in real-time, offering them minute-by-minute insights into energy usage for different processes (Gharaei & Alabdali, 2025). Energy-efficient manufacturers make decisions based on the insights derived from this energy usage tracking system and avoid any wastage of energy (Krishnamoorthy et al., 2023).

Real-time energy monitoring and management through IoT has several advantages for energy savings. This includes monitoring energy trends on a real-time basis and taking necessary steps for energy optimization by pointing out inefficiencies and peak energy consumption trends (Kareem & Rajesh, 2025). In addition, energy management solutions across IoT enable predictive modeling that helps predict energy demand and subsequently modify operations accordingly to avoid energy overuse (Vijayakumar, 2023). For instance, energy-depleting IoT can automatically modulate machine speeds, implement shutdowns during non-operational periods, and even activate other sources of energy if energy demand peaks (Safa et al., 2023). This has major savings and efficiency impacts on the sustainability associated with the manufacturing process.

Many case studies demonstrate the effectiveness of IoT in the area of energy management in the manufacturing industry. For example, IoT applications at automotive manufacturing facilities as shown in figure 3 involved the use of sensors to monitor energy consumption on different production lines (Rajalingam et al., 2024). The project resulted in real-time modification of energy consumption and ensured that there was an overall reduction of 20% in energy consumption (Saini et al., 2024). Another case study involved the application of IoT at food processing facilities to monitor energy consumption at the machine level. The application aimed to enable the identification of machines that consume higher amounts of energy and modify machine operation to consume lower amounts of energy (Kumar et al., 2023).

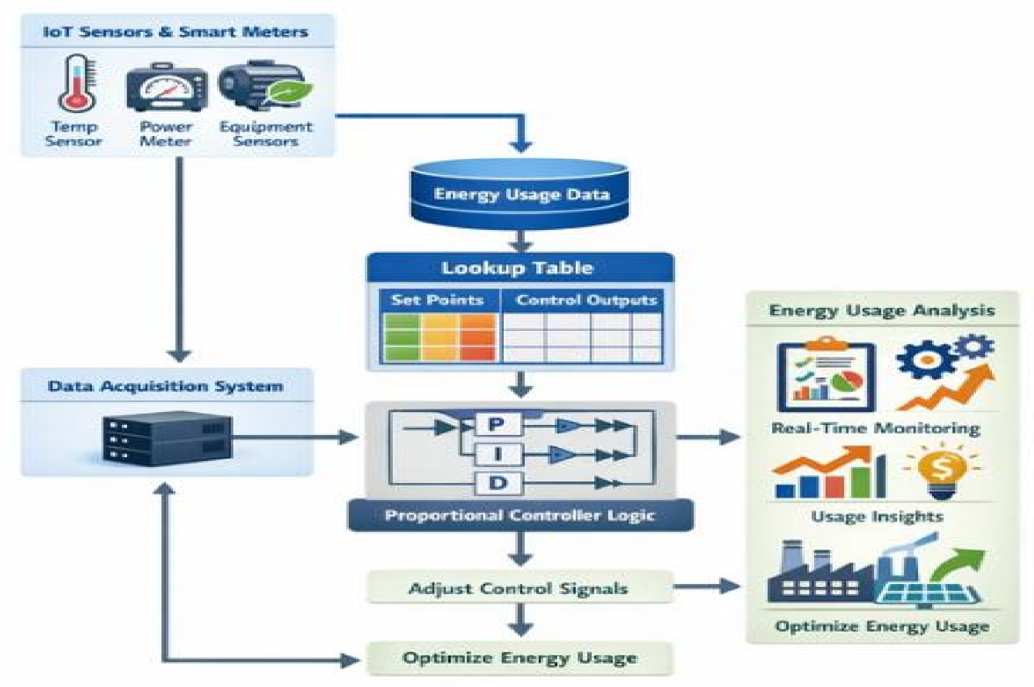

Figure 3: Lookup Table-Based Proportional Controller for IoT

2.3 Limitations and Challenges of IoT in Energy Efficiency

Although there are many advantages that IoT can offer in optimizing energy efficiency in manufacturing, there are still some limitations and problems that manufacturers face in adopting this technology. One of these problems is related to data security and privacy issues. The fact that many types of IoT devices are continuously monitoring huge amounts of manufacturing process data raises a concern about protecting this information from different cyber threats (Alshammri, 2025). The presence of a larger number of nodes within IoT networks can also raise issues concerning different cyber threats, hence requiring manufacturers to adopt proper cyber security practices (Prakash et al., 2024).

A further challenge that will be crucial to the success of IoT adoption in industries will be the interoperability of various devices and systems available in the IoT domain. In an industry setting, various machines and devices will likely belong to separate companies, with each device employing proprietary systems and communication interfaces (Xu et al., 2024). This will make it problematic to achieve seamless integration of IoT systems throughout the production floor, as reported to result in inefficiencies and complexity in energy management. According to (Lekhraji et al.,2024; Rejeb et al.,2023), industries will require publicly available standards and platforms to address this challenge.

Lastly, concerns related to the reliability and latency of the network could also have an adverse effect on the efficiency of IoT-based energy optimization systems. Being IoT-based, the continuity of communication among the devices and cloud services is a key requirement. Therefore, in the event of a disruption to the network or a lag in the communication of data, the efficiency of the management of the energy could be inefficient (Jabeen et al., 2023). Therefore, there could be a lag in the reaction to the changes in the level of the demand for energy, thus reducing the efficiency of the use of IoT for the optimization of the use of the energy (Kumar et al., 2023).

2.4 Fundamentals of Energy Efficiency in Manufacturing

2.4.1 Energy Use in Manufacturing Processes

Consumption of energy in manufacturing processes is one of the most significant operating expenses for most manufacturing industries. Manufacturing, by definition, is an energy-intensive process due to the different manufacturing processes being undertaken, from the handling of raw materials to the end manufacturing of products. Rejeb et al. in 2023 pointed out the significance of energy management in manufacturing due to the different manufacturing processes being undertaken, which consume substantial amounts of energy and require the constant operation of machines and systems.

Consumption of energy in manufacturing processes is mostly cyclic, with peak consumption of energy during the manufacturing process, resulting in the consumption of substantial amounts of energy. This cyclic consumption of energy in manufacturing provides an avenue for the optimization of energy, using the different benefits offered by the IoT in the manufacturing process, as discussed by Gharaei & Alabdali in 2025. Energy used by the manufacturers includes diverse sources such as electricity, thermal energy (for heating and cooling), and mechanical energy (for operating machinery and equipment). According to Safa et al. (2023), the most used form of energy used by the manufacturers includes electricity that powers different machinery and equipment such as motors and conveyors. The use of thermal energy is prominent in metalworking industries, cement production, and food production factories that employ heating equipment and furnaces on a large scale (Krishnamoorthy et al., 2023). Thermal energy can be obtained from different sources including natural gas, biomass materials, and electricity. On the same note, the use of another form of energy called mechanical energy to power heavy machinery using compressed air or hydraulics intensifies the different sources of energy that should be optimized (Rajalingam et al., 2024). In a production setting as seen in figure 4, some of the most prominent energy-intensive systems that must be identified as part of energy conservation efforts include the use of motors, the use of HVAC systems, and lighting systems. Motors use the most energy in many production units because they power most machinery and conveyor systems (Kareem & Rajesh, 2025). Next, when one considers energy-intensive systems, one would have to include the use of HVAC systems, whose main role is to control temperatures as well as ensure that the quality of the air within the production systems is optimal (Saini et al., 2024). Lastly, lighting systems, particularly those used within production, use a remarkable quantity of energy, particularly if incandescent illumination systems are used (Kumar et al., 2023).

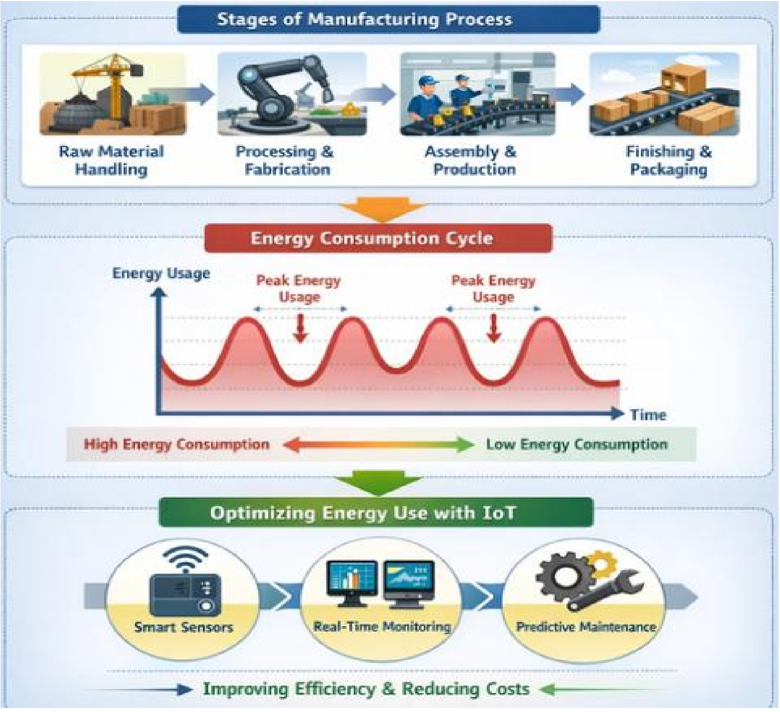

Figure 4: Energy Use in Manufacturing Process

2.4.2 Factors That Influence Energy Efficiency

There are various factors that affect the energy efficiency of manufacturing systems, and these factors need to be addressed properly for optimizing energy consumption. Designing and optimizing the processes for manufacturing is one of the key factors that affect energy efficiency. Optimized design helps reduce energy waste by eliminating non-value-adding processes during the design stage of production, thus optimizing the production processes by eliminating any redundant processes that waste energy (Sikarwar & Tomar, 2023). Optimizing processes, according to Li et al. (2024), helps reduce energy-wasting processes like over-heating/over-cooling, idle time, or optimizing the coordination between processes.

Another important aspect that plays its part in energy efficiency is the efficiency of equipment and machinery. With time, the efficiency of machinery may decline due to the normal wear and tear process and inefficiencies in the way it is maintained. This results in higher energy use (Rejeb et al., 2023). Maintaining the machinery and upgrading from time to time to use energy-efficient machinery will be helpful in ensuring optimal energy use within the manufacturing system. Moreover, use of energy-efficient machinery, such as variable-speed drives for machinery and energy-efficient compressors, can also be helpful in curtailing energy use within the industry (Vijayakumar, 2023).

Additionally, there are environmental factors that may influence energy consumption. For instance, temperature, humidity, and even the location where the manufacturing plant is set up may all influence just how much energy consumption will be required for heating, cooling, and ventilation (Gharaei & Alabdali, 2025). For example, countries closer to the equator may end up using much more energy in air conditioning systems in their manufacturing plants compared to countries where it is cold and they, in turn, might use much more energy for their heating systems in manufacturing plants since they will spend more executing manufacturing operations in cold environments (Saini et al., 2024).

Another major concern on the manufacturing front is energy waste. This is where, despite being old, some factories are working with outdated equipment and inefficient systems where energy is wasted. Lack of real-time monitoring, as highlighted by Safa et al. (2023), results in equipment being used for extended periods, overheating, overcooling, as well as illuminating. To minimize energy waste, it is imperative for factories to implement improved ways of working, real-time energy monitoring software, as well as making necessary modifications to equipment (Kareem & Rajesh, 2025).

2.4.3 Benefits of Energy Efficiency Optimization

There are several advantages of increasing energy efficiency in the production sector, some of them not only confined to saving and cost reduction but also in relation to pollution impacts and competition on markets. The greatest benefit of the use improvement is associated with reduction in costs which a company would otherwise have to pay for its production. According to Prakash et al. in 2024, “manufacture is an expensive business—

energy costs comprise a large proportion of manufacture's costs." Accordingly, higher the optimal utilization of energy by a firm, the smaller should be expenditure on this aspect and thus more profit maximization (Saini et al., 2024). Besides it being an economical derivative, the enhancement of energy usage is closer to more sustainable lessening of the magnitude of pollution induced due to processing. When the usage of energy is reduced, it minimizes the use of fossil fuel, gases associated with environmental pollution of manufacturing processes. According to Li et al. (2024), the benefit of clean usage of energy in the industry results in actual 226 emission clash-discounts of firms on the environment and climate. Conversely, with lower energy use firms' practices are realized in line with the global environmental laws and standards being the number one in terms of the corporations' environmental sustainability (Krishnamoorthy et al., 2023). All this come out the way of demand from present customers of companies (Kareem & Rajesh, 2025).

Regulatory and compliance factors may also play significant roles as positive motivators in the optimization of energy efficiency. In the face of governments around the world increasing their efforts to pass energy consumption and emissionw related legislation, manufacturers can be enforced to switch to energy-efficient technologies and practices (Vijayakumar, 2023). Indeed, those manufacturers having adopted an emphasis on energy efficiency should be able to satisfy these types of regulatory obligation rather than potentially facing penalties in the form of fines etc. At times, companies can even get special incentives like tax breaks for energy-efficient manufacturing facilities.

Finally, it notably contributes in market competitiveness the optimization of efficiency energy. With industry under increasing pressures to reduce costs and become more environmentally responsible, those manufacturers that invest in improving energy efficiency will be the competitive winners. The truth is people are more climate conscious, they opt for products from companies that pay respects as well as care about the environment (Safa et al., 2023). Moreover, those companies that implement process energy optimization will be in the position to charge competitive prices, have a good brand name and provide their products for eco-conscious consumers (Alshammri 2025).

2.5 Fuzzy Logic and Fuzzy Algorithms

Fuzzy logic is a mathematical approach to model uncertainty and vagueness allowing us to make and apply complex hypotheses more flexible and realistic. Fuzzy sets forms the base of fuzzy logic. Thus, a fuzzy set permits the degree of membership in a set instead of just "yes" or "no" as in crisp set theory. Fuzzy sets are characterized by a membership function, which assigns each element of the universe a value between 0 and 1 to indicate the degree to which it belongs to that set. For instance, in one application of temperature control a fuzzy system can provide conditions such that it assigns some degree of membership to the temperature ranging from 0 (cold) to 1 (hot) as opposed classic control system which evaluates the temperature as either hot or cold. **(Tang et al., 2024).** One of the main differences between classical sharp logic and fuzzy is its ability to treat pure uncertainty or vagueness, which contributes a high degree of characteristics in many systems. In standard logic, all the variables are well-defined and sharp; they must be or true or false; any vagueness leads to poor decisions/over-simplification. But in reality most systems are uncertain and no clear classification is feasible. Fuzzy logic addresses this by introducing the concept of “fuzziness", under which a flipping system can be characterized that boundaries are not clearly defined. For example, rather than saying that a Factory is simply "Hot" or "Cold", fuzzy logic can allow imprecise definitions such as "sort of hot" to take on real values between 0 and 1 purportedly offering more degrees of freedom in control, and finer resolution in decision making (Zadeh, 1965; Tang et al., 2024). Ambiguity and uncertainty are the well-known properties in many engineering systems, particularly those associated with human interfaces or natural process. The concept of fuzziness is that which reconciles our perception of uncertainty with computational models and consequently makes fuzzy logic an efficient mechanism in manufacturing, robotics and energy management for example (Saini et al. in 2024. This flexibility is very important in practice because it's rarely the case that a system can be described with yes/no logic. The notion of fuzzy optimality is utilized in many different optimization problems where classical optimization techniques are found to be difficult to handle with imprecision or uncertain data. These algorithms are based on fuzzy sets and membership functions, which can handle uncertain, vague, or ambiguous information for decision making and control systems (Kareem & Rajesh, 2025). Typical fuzzy algorithms that are used for optimization comprise systems based on fuzzy rules, FLCs and f uzzy clustering algorithms.

The Fuzzy Rule Based Systems are systems which work based on a set of “if-then” rules that explain as how system should act, given a situation (Zadeh, 1965; Dogan et al., 2025). ' One concludes that if the rules are induced or derived from expert knowledge, or by means of a some kind of empirical observation like statistical analysis on datasets, then they can describe complex relationships among variables which traditional methods cannot model successfully (Zadeh, 1965; Dogan et al., 2025). For example, a furnace’s temperature is controlled by a fuzzy rule-based system using rules such as "if the temperature is low then increase the heat" (though the amount of heating that this might equate to depends on how low one considers 'low' to be) (Tang et al., 2024). Hence, this model would be portable to different degrees of imprecision and ambiguity in the input data (Zadeh, 1965; Tang et al., 2024). Fuzzy logic controllers are another widely used implementation of fuzzy algorithms (Tang et al., 2024). These controllers employ fuzzy logic so as to make on-line adjustments of a system's operation, that is to say they can be used for controlling motor rotation speed or room temperature (Tang et al., 2024). FLCs are successfully applied to the non-linear, time-variant systems where conventional control techniques are inefficient (Tang et al., 2024). These controllers leverage a FIS (Fuzzy Inference System) that consists of rules and membership functions so as to deliver more flexible and accurate control decisions (Zadeh, 1965; Tang et al., 2024). For instance, in energy management systems for optimized control of HVAC systems operation by varying flow and temperature settings on-line based on sensed values for higher energy saving and comfort (Martínez-Rojas et al., 2025). Fuzzy clustering algorithm is widely utilized in the grouping of data points, whose attributes are uncertain or overlapping (Wang et al., 2024). In classical clustering at least, every data points belongs to exactly one group as we will see that in fuzzy clustering this is not the case (Zadeh, 1965; Wang et al., 2024). The softness of cluster membership in fuzzy clustering is particularly useful in fault detection in manufacturing or energy optimization problems where the recorded data are not exact but noisy (Wang et al., 2024; Manchanda et al., 2025). Fuzzy clustering helps in discovering specific patterns or trends from large volume of data-sets and providing improved decision-making accuracy for energy management systems (Wang et al., 2024; Manchanda et al., 2025).

One of the most important advantages of fuzzy algorithms in optimization is their capacity to handle uncertainty and imprecision inherent in data (Zadeh, 1965; Tang et al., 2024). In most cases of practical optimization problems, e.g., the energy-efficient scheduling in manufacturing, imperfect data or fluctuated data are inevitable (Sitahong et al., 2025). Fuzzy algorithms are very good at dealing with this uncertainty and there is more flexibility if the solution turns out to be wrong (Tang et al., 2024). For example, for energy saving solutions, fuzzy algorithms can incorporate variations in production demand, environmental circumstances and charger performance (Mazouzi et al., 2024; Martínez-Rojas et al., 2025). By these, better predictions and more accurate control actions can be made compared to the classical methods (Tang et al., 2024; Mazouzi et al., 2024).

2.6 Fuzzy Logic in Energy Efficiency Optimization

Fuzzy logic is an important technique to achieve energy-efficient operation of manufacturing systems, especially when the working environment is high in complexity, nonlinearity and uncertainty like IoT-integrated factories. According to Krishnamoorthy et al. (2023), there are three primary mechanisms which allow fuzzy logic to improve energetic efficiency: a) more nuanced control systems. Most of the classical energy management systems will rely on simple ON/OFF switches or linear control systems, which may not be able to handle the extreme complex behaviour of today's manufacturing processes (Das & Dwivedi, 2024). By contrast, fuzzy logic supports smooth and continuous control, which optimally adjusts energy consumption in real-time.

Fuzzy logic is well suited for energy efficient optimization in IoT-enabled manufacturing, as it can handle a large amount of data from various sensors and devices while considering the uncertainty of energy usage. Fuzzy control algorithms might be used, for example, to modify heating and cooling in the factory's HVACs according to temperature and number of machines working. This programmability makes it efficient to apply energy with a minimum amount of waste, particularly in such places where the demand for energy is quite variable.

GA provides the extensive benefits of fuzzy systems for complicated nonlinear systems like IoT based manufacturing. 1) Fuzzy logic addresses the ambiguity in data which is commonplace in industry. As Li et al. As (2024) stated, in a manufacturing environment the IoT devices produce enormous amounts of data that are mostly noisy or uncertain. Based on this inaccurate data fuzzy algorithms are employed for achieving energy optimization, however traditional approaches have little scope in coping with such imprecision. Moreover, fuzzy algorithms are adaptive to some extent then the behaviour of a system will at least induce an adaptive functionality from an AI after training by recording the original implicit knowledge base; not much re-training or even re-programming is necessary, Saini et al. (2024). Such an adaptiveness is crucial for controlling the dynamics involved in the manufacturing environment, where energy requirements could be highly variable over a very short term due to production scheduling, machine condition and environmental situations. Fuzzy logic has been practised successfully in energy management as can be seen from many examples' cases (Görgülü et al., 2013; Mousavi et al., 2022; Spiegel et al., 2003). The first is for the lighting of a production factory, which decides the level to illuminate according to people and time i.e. by hour that they work there! Fuzzy logic is used to stabilize and improve the performance of wind-diesel systems by solving the nonlinear problems adapted with sliding mode control. In this protocol, the energy consumption of lighting was saved by 30% without sacrificing acceptable lighting levels (Görgülü et al., 2013). It has also been adopted in energy-saving motor drive systems with fuzzy-logic controls where the speeds of motors are adjusted by real-time input values sent to the fuzzy algorithms, saving substantial amounts of energy (Spiegel et al., 2003). As shown in Figure 5, the proposed fuzzy-logic framework for an IoT-enabled factory links operational inputs, inference rules, and adaptive control actions to achieve optimal energy management outcomes such as reduced power consumption, improved efficiency, and sustainable production.

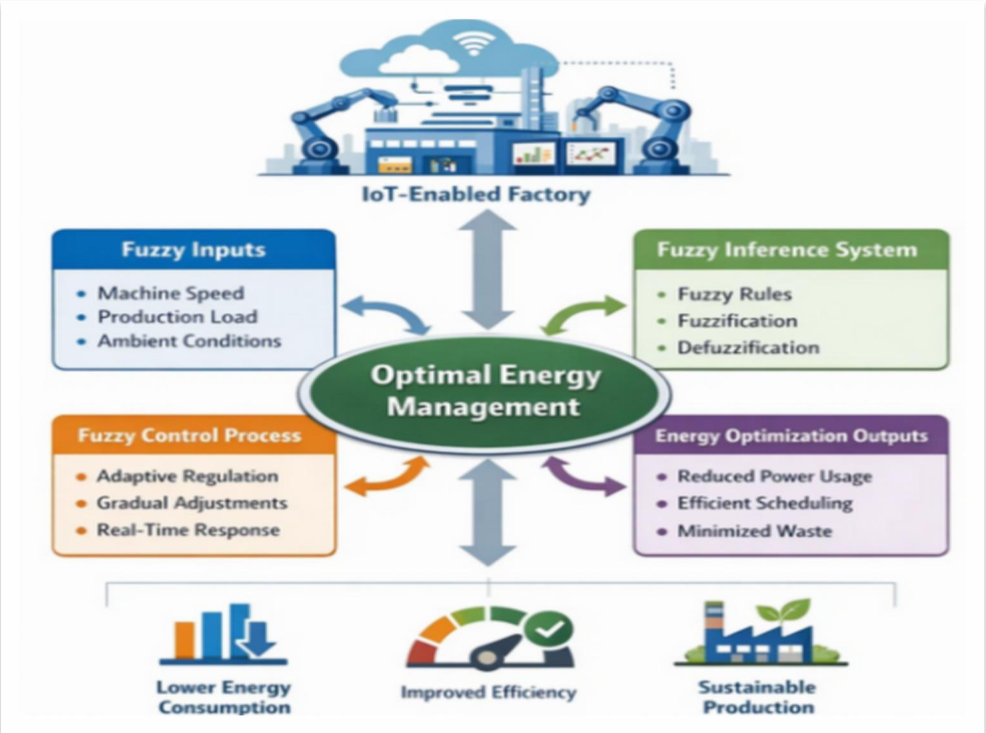

Figure 5: Fuzzy Logic *in* ENERRGY *Efficiency Optimization*

3.0 IoT-Enabled Energy Efficiency Optimization

3.1 Integration of IoT and Fuzzy Logic for Energy Optimization

IoT and fuzzy logic make an effective pair for real-time energy optimization in manufacturing. Thanks to IoT technology, information flows constantly from various sensors placed in production facilities and on equipment. This dataset includes details about the energy use, status of machines and environmental conditions which is very useful for real-time optimization of energy in manufacturing (Saini et al., 2024). Data are passed through a fuzzy logic in which adaptive decision making and control of the machine is implemented, controlling energy consumption at real-time level according to various manufacturing conditions (Rejeb et al., 2023). This application of ICT in manufacturing is to optimize energy consumption in real-time utilizing IoT technology and crisp rules/fuzzy principles.

The acquisition of energy information is accomplished with the help of sensors/actuators and IoT. This is because sensors monitor energy use at different points in the production process, including machines and lighting systems, providing a more detailed picture of power consumption on the factory floor (Gharaei & Alabdali, 2025). This data is sent to central IoT systems, which can process the information and act on it. This is in turn followed by active control of the operation of energy-using systems using actuators based on information obtained from the sensor data. E.g., in an air conditioning system, the sensor can sense a temperature change and the actuators will be capable of controlling the heat or cold required such that energy usage is optimized (Kareem & Rajesh, 2025).

FS are the backbone of IoT and the coupling with FL in energy optimization. For example, a fuzzy inference system may receive the IoT sensor data and generate respective control actions which enable the use of different systems to varying extents according to the IoT sensor data (Krishnamoorthy et al., 2023). Consider an example: in the industry, a cIoT-sensor is employed in production for the IoT-FL coupling of energy saving. FIS can achieve efficient utilisation of energy by controlling the speed of machines, illumination levels, heating and cooling systems with real-time information collected by IoT sensors to effectively manage energy using only when it is needed to be done in industry to reduce waste of energy (Vijayakumar, 2023). Figure 6 shows the IoT–fuzzy logic architecture for energy optimization in manufacturing. The framework combines sensor-based data collection, fuzzy logic processing, and adaptive decision-making to enable real-time energy adjustment, optimal machine control, and reduced energy waste

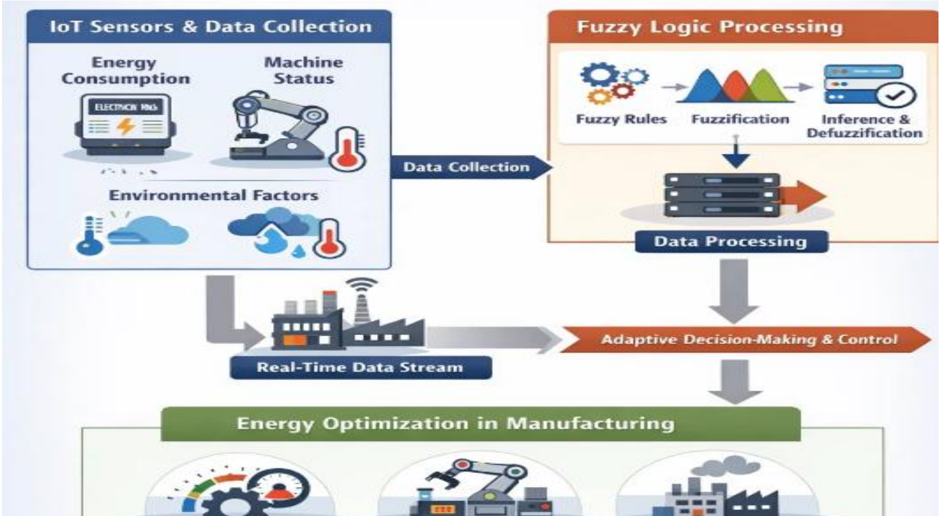

Figure 6: Integration of IOT and Fuzzy Logic for Energy Optimization

3.2 Fuzzy logic-based iot energy optimization framework

Fuzzy logic control system for IoT energy optimization can be further developed from an integrated system which is a combination of the sensors, fuzzy systems and actuators. Such systems have quite complicated components. For instance, IoT sensors need to gather real-time numbers about energy consumption, production levels and any other sort of operating variable. These data are analyzed by means of fuzzy systems, and the actuators send commands to the energy consumption system scaling its operation variables (Li et al., 2024). The system is based on some rules that take into account the fuzzy nature of energy information, for example "when hot and machine runs at full load, reduce energy consumption by reducing cooling power". An illustrative case in application of the IoT-fuzzy logic model for energy optimization is the case of an intelligent lighting system. Occupation and light sensors are addable inside companies, which control the presence level and also the brightness situatzion. This data is fed to the fuzzy controller. Dimming levels of the illumination can be controlled in accordance with fuzzy logic. This will be assist in maximizing efficient energy use- by applying data only when needed and at the optimal required levels (Safa et al., 2023). For instance, when the machine need to operate as full and in enough light conditions, the system can turn off some lights that is present in a room with nobody. Similarly, fuzzy logic control can be applied to the HVAC system. It is able to adjust the airflow system by temperature control. This will maximize energy, reduce its utilization, and without affecting efficiency (Kareem & Rajesh, 2025).

The benefits of such a holistic approach are numerous, the main advantages of this as in the potential for efficient dynamic energy control. Combining IoT with fuzzy logic allow the manufacturer to adaptively respond to the non-stationary environment of this case, in real-time, by minimizing energy consumption while taken into consideration other variables. The energy use system is flexible enough to use the energy when it is needed; savings in addition to environmental impact are significant (Gharaei & Alabdali, 2025). In addition to the benefits, since fuzzy logic system is dynamic and capable of handling uncertainty and vagueness in data, it is more appropriate for a factory environment where energy consumption depends on the production schedule as well as the performance of equipment (Vijayakumar, 2023). Figure 7 presents the operational framework of the fuzzy logic control system for energy optimization. The system integrates real-time IoT sensor data, fuzzy inference processing, and actuator-based control actions to generate optimized control signals for improved energy consumption.

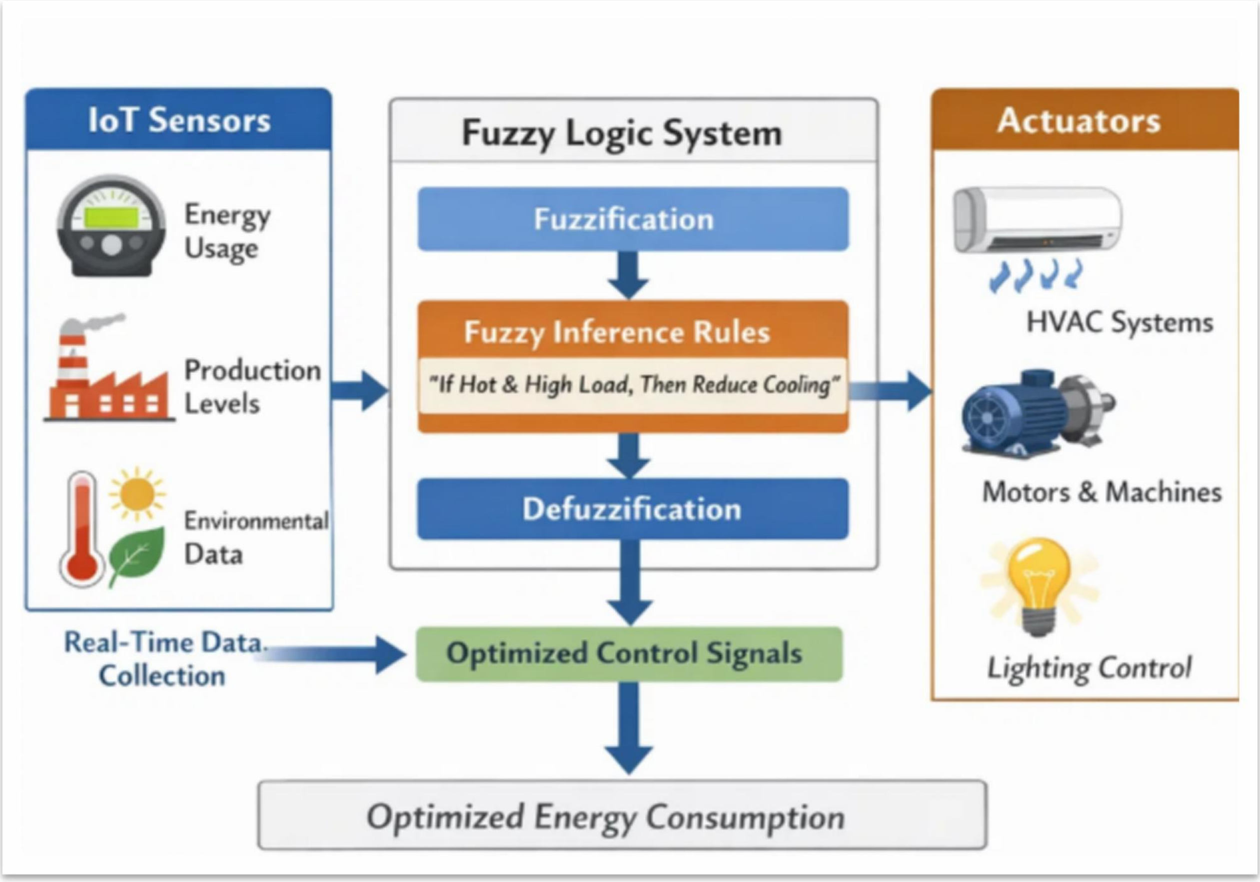

Figure 7: Fuzzy Logic-Based IOT Energy Optimization Framework

3.3 Energy prediction and demand forecasting

Energy demand forecasting is one of the most promising areas where fuzzy logic technology in IoT-assisted energy efficiency can be applied. Energy consumption forecasting plays a crucial role in ensuring that energy used by the manufacturer is optimized without unnecessarily wasting energy. Fuzzy logic systems are effective in energy consumption forecasting tasks as they are able to cope with uncertainties contained in energy consumption datasets. According to Li et al. (2024), predictive modeling of energy consumption through IoT datasets enables energy consumption forecasting and enables the manufacturer to make adjustments accordingly. Energy consumption can be forecasted through various variables such as production schedules, weather, and performance of machines, and energy utilization can be managed to ensure that energy is not wasted through overconsumption. Fuzzy-based energy prediction systems rely on past energy usage, current energy usage, and a set of rules from a fuzzy system to provide predictions of expected energy usage in a factory in the future. These systems have the ability to include several factors, including equipment performance, temperature, or even worker dynamics, within their predictive systems. For instance, a fuzzy system can provide predictions of peak usage in energy in a factory during high usage periods, allowing a factory to make provisions in advance through adjusting machinery speeds, minimizing lighting usage, or in some cases, carrying out proactive maintenance schedules that will enhance energy usage efficiencies (Saini et al., 2024). Fuzzy prediction systems can also aid in energy inefficiency identification by allowing systems to identify patterns in energy usage that are not normal, thus allowing corrective measures to be taken in advance (Safa et al., 2023). Some case studies have proved the success of fuzzy systems for energy prediction for different industries. In one such case study, a fuzzy prediction model was employed for predicting energy demands based on real-time inputs from temperature, humidity, and production processes being monitored by IoT devices. The fuzzy prediction model helped the textile manufacturing unit identify energy peaks during certain production processes, enabling the unit to adjust its processes for energy savings, which led to a reduction of 15% of energy utilization (Rajalingam et al., 2024). Fuzzy prediction was also employed for predicting energy demands for a metal processing industry, whose production levels and furnace temperature were being monitored continuously. Fuzzy prediction helped minimize energy expenditure through optimized heating for furnaces, thereby preventing waste energy utilization during non-peak times (Vijayakumar, 2023).

3.4 Challenges and limitations of iot-fuzzy integration

Despite this possible good potential that could be offered by integrating both IoT and fuzzy logic approaches in order to optimize electrical energy still, there are however some limits challenges which must be addressed. The first challenge to be met concerns the real time data processing and computational expense of fuzzy logic. The Internet of Things being able to create big data from multiple sources through different sensors indicate that real time processing of the data is going to be computationally intensive (Krishnamoorthy et al., 2023). Thus, the bottleneck in processing large dataset timely has to be resolved using fuzzy logic (Gharaei & Alabdali, 2025). The last limitation has to do with scalability and complexity to deploy a fuzzy logic system in a large IoT network or systems. The reason is that the higher extended growth of IoT networks, more sensors and device and sensor data products there is complexity to manage and optimize energy consumptions. The fuzzy logic system and the training set which might have performed well in a small type unmanned system network, may not have the capability of handling large amount of dataset and making decision in a large scale system or networks (Rejeb et al., 2023). This problem could be resolved by having better computing facilities and/or performing more efficient fuzzy algorithms that can handle higher numbers of sensors in IoT networks. The question of compatibility in the context of various IoT protocols and fuzzy logic systems also needs to be addressed. However, there could be an endless variety of IoT technologies, some based on different types of communication protocols, which could turn the inclusion of those in one and the same fuzzy logic energy optimizing system to be challenging (Vijayakumar, 2023). Thereby, it could be interesting to bring together different IoT technologies in effective communication with fuzzy based logic systems or platform by using standardize communication platforms or technologies (Saini et al., 2024).

3.5 Energy Efficiency in Smart Factories

IoT And Fuzzy Logic Combined Smart Factories work to Overall Increase the Efficacy of Energy Consumption in Several Industries Benefits gained Base on IoT inside smart factories with fuzzy logic are very high. One such example in this line is the energy management system of an automotive industry smart factory, which include IoT sensors and fuzzy logic algorithms to collaboratively manage the energy consumption on a real-time basis (Vijayakumar, 2023). For the proposed energy management system, IoT sensors were deployed in-situ within smart factory for monitoring of the various parameter such as temperature, humidity, machine efficiency and energy consumption at machine level. These terms on their turn sent all of the parameters to a centrally connected platform in which a fuzzy logic algorithm decided about energy distribution according to some predetermined rules of the fuzzy logic method. The fuzzy logic controller was implemented to work on subtle rules as policy wrapped around 'specifically electricity usage pattern varies dynamically'. For instance, the fuzzy logic controller allowed for control of lighting and HVAC conditional to whether workers were in the manufacturing section (production area) of the plant and outdoor weather. When those machine work conditions were met, i.e., high temperature within the factory and all machines operated to maximum capacity, the controller for example was adapted to better control air flow rates and temperatures in HVAC systems provided for those machines. Additionally, the controller was programmed to switch off the lighting in unoccupied areas so as to reduce energy consumption (Saini et al., 2024). Among the advantages was significant energy savings due to the IoT-fuzzy logic integration. According to the result of implementation, 20% of overall energy consumption in the smart factory has been cut down. It resulted in significant cost-savings & reduction of adverse environmental impacts of the facility‘s operations (Gharaei & Alabdali, 2025). Other advantages of utilizing it were improved management and control which resulted in an efficient use of resources. Also, the overall environmental impact of the facility's operations also became more positive by the fact that the site's carbon footprint was less.

3.5.1 Industrial IoT and fuzzy logic in hvac systems

Another promising application of IoT and fuzzy logic in energy efficiency is in the HVAC systems at manufacturing plants. It's simply because heating and ventilating systems are necessary for comfortable working conditions but they also consume huge amounts of electricity. In a similar instance of application of IoT in textile mill, where IoT based sensors were interfaced with the HVAC system for real time monitoring of temperature, humidity and air quality were used (Krishnamoorthy et al., 2023). This data captured from the sensors activated a fuzzy based control system to minimize energy usage while maintaining favorable atmosphere for human and machine as per predefined fuzzy rules. The fuzzy logic controller integrated time, outdoor climate conditions, production plan and inside temperature by means of the membership functions and adjusted online the operation condition of HVAC. For instance, when there is no production, and less employees are available it has the plant at its minimum cooling or heating based on the outside temperature which results in lower energy consumption (Kumar et al., 2023). The fuzzy system could adjust air flow to the humidity and air quality in order to assure energy was cost-effectively used, but without sacrificing the quality of the ventilation. The outcomes of the work were highly encouraging. It contributed to considerable energy savings at the manufacturing unit, where 15% of energy used for HVAC applications was saved leading to overall massive reductions in its utility bill (Safa et al., 2023). Besides saving energy and using the heat more effectively, this improved control over temperature provided better working conditions for labourers — in turn fuelling greater worker productivity and reduced machine wear and tear. So, the present case study conscientiously discloses that there is a possibility of using IOT and fuzzy logic in various operations within manufacturing plants for energy savings.

3.5.2 Predictive maintenance and energy efficiency

Predictive maintenance IoT solution involving fuzzy logic has also been introduced for ensuring optimal maintenance planning and energy conservation in industries. In another application example in an electronics manufacturing plant, IoT devices were used to facilitate the condition monitoring of motors, pumps and conveyor systems. The conditions of the machines are constantly tapped, i.e., temperature, vibration and pressure; they are then processed using a fuzzy logic technique to predict machines' maintenance (Rejeb et al., 2023). The fuzzy logic system utilized data from these instruments for not only the prediction of maintenance needs but also the optimization of executing them. In its ability to predict maintenance actions well in advance of any machine failure – the system reduced down time that was costing energy at high levels because of poor performance from a machine. In any system like the conveyor, the fuzzy logic system by its predictive maintenance check to make sure that it slows down the speed of a conveyor so as not to overwhelm its motor, for example. This was inevitable as overloading would at present be linked with increased energy usage (Kareem & Rajesh, 2025). This predictive maintenance solution had an impressive impact on factory energy efficiency. Due to reduction in downtime and optimal condition of machines, factory could reduce its energy consumption by 18% along with enhanced production throughput (Saini et al., 2024). Third, the expense to maintain the factory went down due to less emergency repairs and improved labor control. In the present case study we aim at keeping the machine efficient and preventing loss of energy during its unproductive use which is triggered by fuzzy logic IOT In predictive maintenance not just managing efficiency of the factory but also controlling waste management that can incur by it.

3.6 Challenges and future directions in iot-fuzzy energy optimization

Although integration of IoT and fuzzy logic has great potential for improving eco-efficiency in manufacturing, some challenges have to yet be resolved so that industry could widely apply them. A major challenge is the Big Data processing and complexity of computation when it comes to IoT and fuzzy systems. The abundance of data created by IoT devices in extensive factories can be too much for older computing infrastructure, when real-time processing is needed. The fuzzy logic algorithms are required to deal with huge amounts of data from sensors and to take decisions on time, which would place a burden on computational resources and slow down decision-making process (Li et al., 2024). Scalability is another challenge. With the rise of IoT networks and an increasing number of sensors to monitor various systems in a manufacturing plant, comes more complexity in keeping track of and optimizing energy-demand. The larger and more complex fuzzy systems might not be able to easily scale in large size of the industrial environment, while a number of energy-consuming systems need to control at the same time (Vijayakumar et al. 2023). To address this issue, more scalable fuzzy algorithms need to be developed and computational infrastructure should be enhanced. The compatibility of the fuzzy logic systems with IoT devices is another issue in this research. In the majority of manufacturing plants, IoT devices are provided by different vendors in order to prevent accelerator monopoly and may employ disparate communication protocols which become an obstacle in their integration into a single network implemented for fuzzy logic-based energy optimization system (Saini et al., 2024). The issue can be also tackled by enforcing the standardization of communication protocols and leveraging open-source platforms to facilitate the endless integration of heterogeneous IoT devices with fuzzy logic-based systems. In the future, AI and ML can be incorporated with fuzzy logic to achieve better energy optimization in ItoT-enabled environments. As an AI and ML tool, they offer a feature in the decision-making process of fuzzy systems because decisions can be learned from previous data and updated to reflect changing conditions without human intervention (Safa et al., 2023). For instance, machine-learning models can make more accurate energy-demand predictions and fuzzy logic systems can use these to adjust operations. These technologies together would result in smarter and adaptable energy management systems, ultimately enhancing the effectiveness of the IoT-fuzzy systems for real-time energy optimization (Krishnamoorthy et al., 2023).

4.0 Advanced fuzzy techniques for energy optimization

4.1 Fuzzy neural networks for energy efficiency

FNNs, an innovative hybrid methodology that integrates the merits of fuzzy logic and ANN for addressing intricate energy optimization tasks in IoT-based manufacturing systems. Fuzzy logic permits systems to handle uncertain and imprecise information, while neural networks are particularly good at learning from big data and predicting patterns in data. Combining these two methods provides an effective way of managing energy, especially in the manufacturing field when systems are mostly nonlinear, dynamic and uncertain. Fuzzy neural networks (FNN) combine some parts of fuzzy logic such as rules and membership functions with the learning capabilities of neural networks. It allows complex data from IoT devices to be processed and analysed, such as those created by sensors that track energy usage, temperature, machine performance and an array of other metrics. The FNNs integrate ANNs with fuzzy logic for decision making, in which the neural networks make decisions on historical experience of training and real-time feedback based on fuzzy inference. "An FNN, for instance, could predict the amount of energy used in the future based on past power consumption patterns as well as switch machines to a lower level or adjust the incoming power supply that minimised wastage but kept operations maximised within factory." FNN's have been applied to several types of energy optimization jobs in IoT-based manufacturing systems. For example, in a manufacturing plant, the HVAC systems have been controlled efficiently through FNNs by modifying heating or cooling output with respect to current sensor readings as well as their past values (Vijayakumar, 2023). This hybrid nature of FNNs provides more accurate prediction results of energy demand and makes it possible to establish dynamic and adaptive control strategies to improve energy efficiency without compromising the system performance (Gharaei & Alabdali, 2025). Advanced systems are also able to learn from new data all the time and adapt their strategy as conditions change, a must-have for energy efficiency in the fast-moving environment of today's manufacturing plant. As presented in Figure 8, the integration of fuzzy logic and artificial neural networks forms a fuzzy neural network framework for IoT-enabled manufacturing. This approach combines fuzzy inference with data-driven learning to improve energy consumption prediction, optimization, and intelligent control in manufacturing systems.

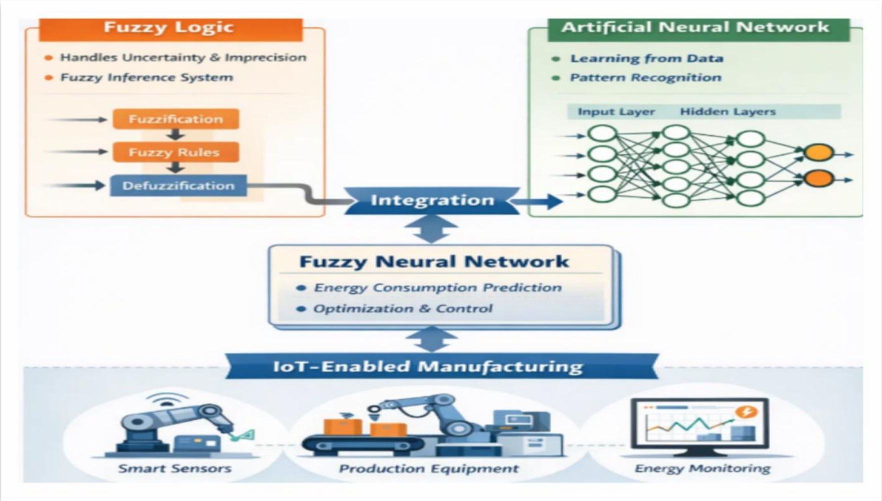

Figure 8: Fuzzy Neural Networks for Energy Efficiency

4.2 Adaptive fuzzy systems for real-time optimization

The adaptive fuzzy systems are systems, which adapt themselves and their rules, decision mechanism based on the sensed data obtained from IoT. These systems share certain common characteristics such as the ability to learn and adapt over time with respect to modifying environmental conditions or operations demands, which is why they are perfectly suited in real time for energy optimization of manufacturing systems (Rejeb et al., 2023). An adaptive fuzzy system will be created to adapt the fuzzy rules or membership functions with the new data without manual intervention and any reprogramming. This is important in specific applications where energy consumption must be minimized and the demand rapidly changes locally in the environment, i.e. a manufacturing plant having changing production schedules or other outdoor environmental ambient factors. For instance, an adaptive fuzzy system installed in a factory can control machine speed, lighting and HVAC depending on instant data of the quantity of workers, ambient temperature, and machine load. This dynamic optimization minimizes wastage as energy is consumed based on the real demand. An important characteristic of the adaptive fuzzy systems is a self-learning and real-time adaptation. Towards that end, these systems can constantly act as they are fed fresh data on energy consumed and be able to monitor for trends and pattern of energy consumption thereby making themselves very effective at switching usage patterns over time. A semiconductor manufacturing plant, for instance, may have an adaptive fuzzy system that learns from previous temperature data and adapts the cooling system to operate at lower energy consumption (when it becomes idle) on a time-of-day basis. These systems enable energy saving without humanintervention from time to time (by which operational costs decrease and overall system's performance are increased). Industrial ovens and compressors are examples of these adaptive fuzzy systems. For an example, the industrial ovens of a specific food processing plant were optimized by means of an adaptive fuzzy logic system. The handheld device heated the bedding to a predetermined temperature in real time under adaptive fuzzy control, with adjustable heating levels and durations according to sensor inputs, it could automatically adjusted by learning from previous different cycles for any calendar change of the production schedule. One such system is said to result in as much as 20% less energy use, yet maintain quality and mitigate environmental impacts of production. Figure 9 illustrates an adaptive fuzzy system for energy optimization in IoT-enabled manufacturing. The framework integrates IoT sensor inputs, fuzzy logic, learning and adaptation, and real-time data analysis to support continuous feedback, system adjustment, energy efficiency, and production optimization.

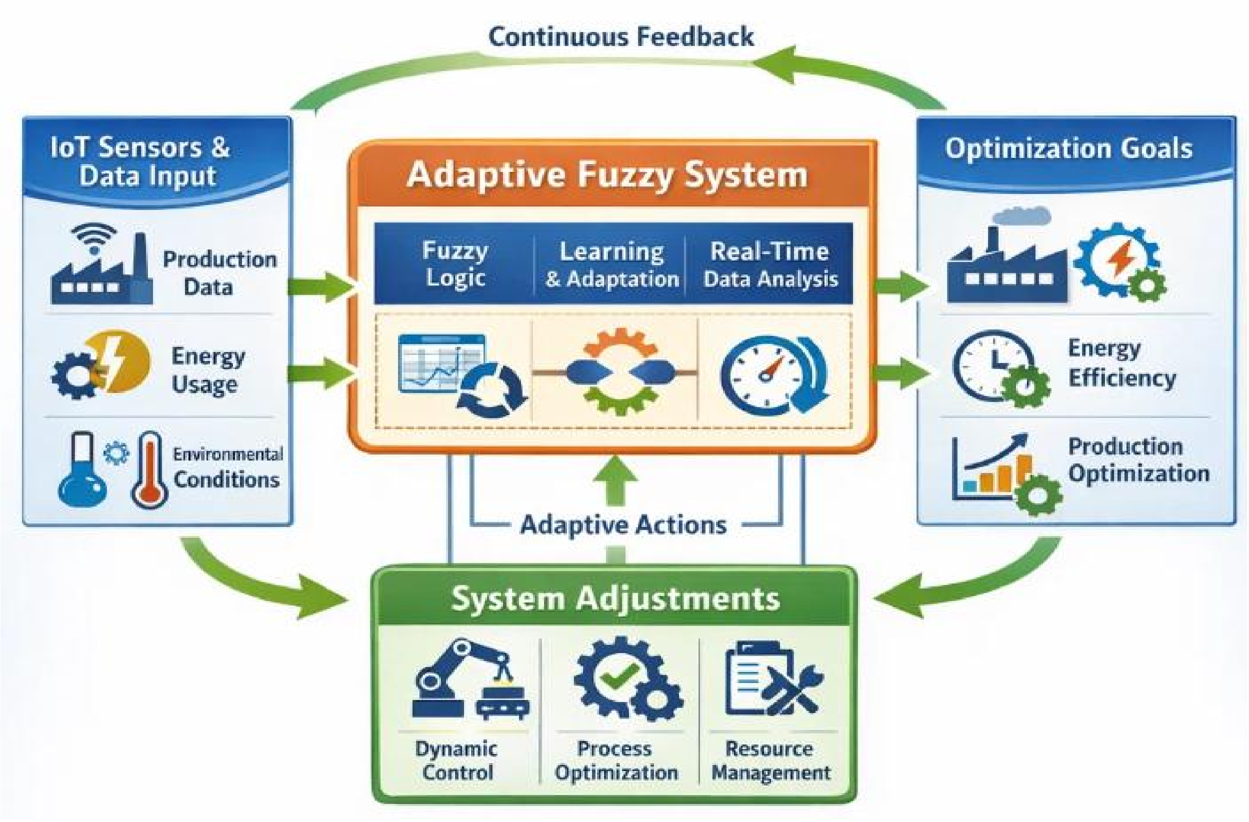

Figure 9: Adaptive Fuzzy Systems for Reaal-time Optimization

4.3 Fuzzy clustering algorithms for energy optimization

Fuzzy clustering, from a process perspective, can be applied while grouping datasets at similarity level; why enabling systems to expose energy consumption patterns that would have been missed or were buried when analysed in the conventional manner. Conventional clustering assigns each datum to one category, while fuzzy clustering as a method also allows to assign them to more than one cluster in proportion of memberships which plays an important role for energy-conserving dynamic systems like e.g.

manufacturing floors (Krishnamoorthy et al., 2023). In terms of energy optimization, fuzzy clustering methods may be utilized to find the areas of inefficiency in terms of energy use by making use of the data collected from IoT sensors on past and present level of consumption; for instance if an overconsumption of certain machines or a specific mould process has been identified whilst comparing it with other simulation results intensities between groups can facilitate a manufacturer to classify that some machinery inside their plant is consuming higher than what it should (Rajalingam et al., 2024). For example, in a factory some production lines of it might schedule to consume - in the point of view of fuzzy clustering algorithms - constantly more energy during off-peak time and be subject to optimization through machine parameters as well as through machines' running time or manufacturing process. Fuzzy clustering has been successfully used for energy optimization in some case studies. Another application to a data set was a fuzzy clustering algorithm applied on non-statistical information that came from the IoT (Vijayakumar, 2023): in this case, in a large electronics production plant monitoring of electricity consumptions between different machines were monitored using IoT sensors and sewing them into clusters according to their patterns. Then the clustering algorithm indicated energy consumptions of individual machines during non-peak time. Energy consumption was reduced by recommending how the machines should be operated. This resulted in an energy saving of 12% without a major impact on production (Saini et al., 2024).

Fuzzy clustering was also applied as a case study in a steel plant to optimize energy utilization for the furnace process. Using fuzzy model in ME and MEm measurement of energy was due to clustering pattern observations in ME and MEm intensity levels under the processes of steel making method, which was also effective in detection of wastage efficiency at the furnace level, regardless the time load flexibility (Gharaei & Alabdali, 2052). Figure 10 illustrates the application of a fuzzy clustering algorithm for energy efficiency improvement. The framework shows how energy consumption data are processed through fuzzy clustering to identify usage patterns, assign partial membership across multiple clusters, and support optimization strategies aimed at reducing energy consumption, lowering costs, and promoting sustainable operations.

Figure 10: Fuzzy Clustering Algorithms for Energy Optimization

4.4 Fuzzy Logic based Multi-Criteria Decision Analysis for Energy Efficiency

Multi-Criteria Decision Analysis (MCDA) is a set of tools and techniques that are used in decision making – to provide comparative information about the different options available to decision makers. In energy efficiency optimization, MCDA approach combined with Fuzzy Logic helps the manufacturers to compromise between energy efficiency and other characteristics such as cost, performance and environmental impact. The use of Fuzzy Logic on the MCDA will allow the manufacturer to take a more optimal decision considering the uncertainty within data as well as trade-offs in other optimized objectives (Krishnamoorthy et al., 2023).

The implementation of the MCDA is also applied to energy optimization problem, where we are interested in comparing various alternatives for saving electricity include replacing equipment, changing operating time and as well as creation of energy-saving technological methods. 120. In the present case, the fuzzy logic relates to "the extent of fuzziness in decision maker regarding options weighed" allowing the decision makers to compare "costs, estimated energy savings and environmental benefits". For example, the fuzzy MCDA is utilized for comparing various possibility of HVAC system optimization according to cost and energy saving effects and environmental effects. Specific drawbacks So far, we have already mentioned some solution concepts to assess the critical aspects of smart city projects (which include IoT integrated energy systems) using fuzzy MCDA techniques: measures for saving energy in smart building and industry. In an example a study is performed on the selection of optimum mix of energy conservation measures for a commercial office building using fuzzy MCDA considering the implementation cost, savings and environmental impact with fuzzy ratings and following reduction stand was observed: 10% lesser collective energy consumption with considerable decrease in carbon emission (Saini et al., 2024).

5.0 Future trends and emerging research

5.1 AI and Machine learning integration with IoT and Fuzzy logic

The combination of AI, ML, IoT and fuzzy logic would present an interesting future to the energy optimization in manufacturing industry. Given the current momentum of data-driven manufacturing practices, a combined utilization of these technologies promises to deliver even smarter energy optimization solutions. Because of the efficiency of fuzzy logic in managing uncertainty and imprecise granularity, it could enhance the learning AI for big data to an even smarter one for energy consumption optimization (Krishnamoorthy et al., 2023). The introduction of AI/ML features can enhance decision making processes in fuzzy logic systems. AI can improve the accuracy of energy demand predictions and patterns of usage, facilitated by more sophisticated algorithms that analyse large data volumes from IoT technology in real-time than were previously applied. This is even more pronounced in dynamic manufacturing environments where energy consumption will change as the manufacturing schedules are changed or machines are down due to certain weather conditions (Saini et al., 2024). Example to 3: For example, deep learning algorithms can be used to analyze energy usage pattern and find better the peaks and troughs in the energy usage, enabling us to adjust energy system well ahead- not necessarily reactively- or preemptive action on this demand (Rejeb et al., 2023).

Moreover, the ML models can be combined with fuzzy logic techniques [3] to learn from the data in order to optimize the process of energy optimization. This is because the system would learn to make better decisions with more exposure. This enables the system to improve its efficiency in energy management over time, without the interference of a human for betterment (Gharaei & Alabdali, 2025). A case study of system optimization satisfied itself with the application / combination of deep learning and fuzzy logic on energy demand prediction and HVAC + lighting system optimization. This resulted in a decrease of 25% of energy cost established that the best operating conditions are not affected (Vijayakumar, 2023). In the future, we expect more and more novel applications of deep learning in fuzzy systems for energy forecasting and management as such AI-powered solutions keep advancing. They would play an important role in realising smart and autonomous systems within the IoT-based advanced manufacturing domains.

5.2 Advancements in IoT and Fuzzy Algorithm Capabilities

Future development in IoT technology, in particular with 5G and edge computing becoming mature, is another that will matter for the optimization of energy efficiency. This is possible because of its ultra-low latency, high speed data transfer and capability to connect multiple devices in the case of 5G which will enable IoT systems to operate in real-time (Safa et al., 2023). In 5G, for instance, the internet of things devices can help in transmitting an immense amount of data coming from the sensors and actuators deployed within industrial plants with a low latency which allows the making of decisions that are energy efficient rather quickly and they can introduce more devices that could connect them through the internet of things technology which makes it easier for analyzing how much energy has been consumed. Another pivotal area in IoT technology, known as edge computing, will allow calculations to occur closer to the source of data generation, thus reducing the distance that information must travel for processing in far-off cloud-computing centers. Moreover, edge computing particularly if integrated with fuzzy logic systems in devices (e.g., IoT) prevents energy control by a center miles away waiting for decisions from remote centers to which are crucial for fast-paced adjustments in energy (Kumar et al., 2023).

Therefore, with the advancement of the IoT, the fuzzy optimization of algorithms has been developed as well. Further research in the developments and applications of more advanced fuzzy techniques (e.g., quantum fuzzy systems, fuzzy optimization) are also being conducted to further enhance ability of fuzzy logic for energy optimization (Rejeb et al., 2023). Specifically, quantum computing may have the ability to solve high-dimensional complex data sets much faster (in orders of magnitude) than traditional computational methods (Gharaei & Alabdali, 2025). More complex optimization problems, such as the energy management optimization by fusing fuzzy logic and quantum computing, become manageable.

Nevertheless, hybrid fuzzy optimization techniques are emerging to exploit the good features of both types of solutions in order to optimize energy utilization such as GAs or PSO and flexibility provided by fuzzy systems (Vijayakumar, 2023). There may be also better solutions using better fuzzy algorithms in the future, which could result in even more optimized use of energy among different industrial units.

But when the size of IoT networks as well as complexity of fuzzy systems increases, there exists challenges in data processing, interconnection and efficiency to be solved for future. Those solutions will come as we evolve AI and machine learning and the infrastructure catches up to support complex systems.

5.3 Global Efforts and Regulations

In the current global manufacturing context where energy efficiency is gaining significance, government policies have been assuming increasing importance in driving the adoption of energy-efficient products. Carbon emission reduction, improvement of energy efficiency as well as eco-friendly manufacturing through laws and regulations are leading the manufacturing industry to implement IoT-based energy optimization solutions. The European Union is concentrating this year on the Green Deal that aims to make Europe the first "climate-neutral" continent by 2050. The manufacturing industry is the focal sector in WEME (Saini et al., 2024). Such legislations and regulations are driving the manufacturers to choose a more energy efficient solution. This intelligent based applications for IoT-fuzzy logic solutions cannot be omitted here. In this context, it is possible that in the US, the Energy Star program (which provides standards for building energy efficiency and manufacturing process efficiency) continues to incentivise green IT despite promoting the greener technology of energy saving products such as IoT systems capable of monitoring and controlling energy use (Vijayakumar 2023). These actions urge manufacturers to invest in energy-saving technologies such as IoT technology and fuzzy logic systems to achieve higher standard of energy-saving requirements. The consequence is that for this manufacturer the relative importance of IoT technology in cooperating with wise energy use is higher.

As a global citizen there exist movement such as the United Nations' Sustainable Development Goals (SDGs) that calls for immediate action of reducing energy usage and sustainability in manufacturing (Safa, Rajesh & Saritha, 2023). Application of integrated energy management is aligned with SDG7 (affordable, reliable, sustainable and modern energy for all) including solutions based on internet of thing. With the continuous promotion of governments to sustainable development, the energy consumption in manufacturing industry is anticipated to be incorporated into more rigorous policies, which will promote the internet of things (IoT) based on 4G technology solutions for an IEM. In addition to government regulations, development of standardization within the IoT and energy management domains is ramping. Normalized communication protocols within the integration level of IOT sensors and fuzzy logic systems may add scalabiltiy to the technology within industrial applications (Gharaei & Alabdali, 2025). The development of worldwide standards in energy efficient IoT would make this available for everyone and subsequently responsive to the manufacture of additional advanced IoT and fuzzy logic applications in energy saving. Given the dynamic regulatory landscape and the progression of IoT technology, such solutions will have a significant impact on consolidation. Guided by the government policies and regulations, in the future of energy-saving manufacture, IoT technology 、 fuzzy logic technology, AI technology are developed and applied widely.

6.0 Conclusion

An interesting use case is adding a Fuzzy Algorithmic layer on top of various sensors adopted by the IoT (which I have written about in a previous blog) to aid manufacturers improve their energy efficiency. Real-time data collecters are integrated in IoT technologies into various sensor devices in the factory floor. The Fuzzy Algorithm is the one in charge of processing this information and taking flexible and adaptive decisions when deciding the way to consume energy. The integration of the two can allow manufactures to consume power efficiently and meanwhile maintain manufacturing quality and productivity. It is worthwhile to mention that the effect in adapting IoT Together with Fuzzy Algorithms on manufacturing found a thrilling one as well as cost-effective in taking decision and reducing the effect of manufacturing's damage on the environment.

The results of this systematic review may serve as the guide for manufacturers to optimize energy efficiency by creating IoT-oriented, fuzzy logic-equipped, or combined energy management systems. The possibility was depending on the strength of data structure and the extent to which IOT modules could think as one, then we had grown fuzzy systems to classify the energy data. Combining the technologies raised computational issues but would justify that cost in the long run.

In the future, potential applications of IoT, and fuzzy algorithm optimization for energy efficiency are even more bright. With the emergence of smart factories, increasing demands have also increased for more sophisticated product-specific self-adapted energy efficiency optimisation techniques. These could be that of hybridizations of fuzzy optimization such as AI or machine learning with the theories of fuzzy optimization, quantum computing for real-time energy efficiency optimization. The emerging possibilities enabled by these technologies also point to a promising future for greener kinds of manufacturing as more energy-conscious and cost-effective ways to manufacture products ‘go green.

7.0 References

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