ENERGY EFFICIENCY OF AUTOMATED MANUFACTURING SYSTEMS: INNOVATIONS, CHALLENGES AND THE FUTURE OF INDUSTRIAL ENERGY

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Nowadays, optimizing energy efficiency is a key factor for the sustainable development of industry, especially in the field of automated manufacturing systems. These systems are design to streamline production and reduce human intervention, but at the same time, they also pose a challenge in terms of energy consumption. This article deals with various aspects of energy efficiency in automated manufacturing systems. It describes the factors that affect energy consumption and identifies technologies and practices that can lead to reductions in energy consumption, costs and emissions. Automated manufacturing systems use robotics, sensors and advanced control systems to optimize manufacturing processes. Thanks to these technologies, production can be faster, more accurate and more efficient. However, these systems can have high-energy consumption, especially in the case of complex and non-optimized processes. Therefore, it is important to use intelligent control and monitoring systems that allow optimizing energy consumption in real time.

KEYWORDS

Energy efficiency, automated manufacturing systems, energy losses, energy consumption, efficiency trends

1 INTRODUCTION

Energy efficiency is a key parameter of modern automated manufacturing systems. With increasing demands for sustainability and emission reduction, improving efficiency is becoming an essential step in optimizing production processes. Nowadays, when the energy intensity of industrial production processes is one of the main factors affecting costs, competitiveness and environmental sustainability, the need to implement energy-efficient solutions is increasing. Automated production systems, which are equipped with modern technologies such as robotics, the Internet of Things (IoT), artificial intelligence (AI) and advanced control systems, offer significant opportunities for improving energy efficiency.

2 THE IMPORTANCE OF ENERGY EFFICIENCY IN AUTOMATED MANUFACTURING SYSTEMS – FACTORS AFFECTING ENERGY EFFICIENCY

Energy efficiency in automated manufacturing systems (AMS) means minimizing energy consumption while maintaining the required quality and performance. Automated manufacturing systems represent a technological advance that allows for cost reduction, increased production and minimized errors. However, energy consumption is often a significant item in production costs. To reduce energy consumption, it is necessary to optimize not only the production process itself, but also the overall management and operation system.

According to a report by the International Energy Agency (IEA), industry accounts for approximately 30% of global energy consumption, with more than 70% of this energy being used to generate heat and power machinery. Therefore, optimizing energy efficiency can significantly reduce operating costs while improving the environmental sustainability of businesses.

Key factors influencing energy efficiency

- Equipment type and configuration.
- Process and material flow optimization.
- Efficient energy consumption management using sensors and artificial intelligence.

Manufacturing automation, which includes the deployment of robots, sensors, advanced control systems, and digital transformation, allows manufacturing plants to increase productivity, reduce errors, and optimize processes. However, these systems, when not properly designed or managed, can lead to inefficient energy consumption. Energy intensity can be caused by a number of factors, such as:

- Inefficient use of equipment and processes: Many automated systems do not optimize equipment performance, which can lead to excessive energy use, for example, when equipment is not in full operation.
- Insufficient operational management: Systems that do not use advanced algorithms to manage energy consumption may show inefficiencies in processes where energy could be saved.
- Losses in energy distribution: In some cases, energy may be lost during transmission or distribution within production lines and equipment.

For these reasons, energy efficiency in automated manufacturing systems is key to reducing operating costs and achieving sustainable growth. Optimizing energy consumption not only reduces costs, but also improves the environmental balance of businesses and helps meet regulatory emissions requirements.

Other factors affecting energy consumption in automated systems

- Control systems and optimization of production processes

Automated manufacturing systems use advanced control systems that coordinate the activities of machines, robots, and production lines. The efficiency of these control systems directly affects energy consumption. Suboptimal settings or poorly controlled processes can lead to excessive energy use, for example, when equipment runs at full capacity when it is not needed. Therefore, it is important to use advanced algorithms for real-time energy management that analyze current production conditions and adjust the performance of the systems [Kuric 2022].

- Energy losses in distribution

Energy losses during transmission and distribution are another important factor that can affect the overall energy demand. These losses arise due to resistance in electrical circuits, poor insulation, unregulated distribution and outdated technologies. Modernizing distribution networks and introducing smart metering systems can help reduce these losses and increase the efficiency of the entire system.

- Equipment and machinery

The energy consumption of equipment and machinery used in automated systems is a key factor. Motor units, drives, compressors, pumps and other equipment consume most of the energy in industrial operations. Improving the energy efficiency of these equipment, for example by using energy-efficient motors and inverters, can bring significant savings [Barnik 2019].

3 ENERGY EFFICIENCY IN THE CONTEXT OF AMS

Energy efficiency can be defined as the ability of a system to perform the required work with minimal energy consumption [Ivanova 2022].

3.1 *Key parameters affecting efficiency*

- Technical structure of the equipment: Older systems have higher energy requirements.
- Energy modes: Proportion of time spent in standby mode and active production.
- Control algorithms: Process optimization using artificial intelligence.

4 ENERGY EFFICIENCY MODELING

The energy efficiency of a system can be define as the ratio between the useful energy used and the total energy input:

$$\eta = E_{useful} / E_{input} \times 100\% \quad (1)$$

Where:

- E_{useful} is the energy used for production,
- E_{input} is the total input energy.

4.1 *Energy consumption breakdown - Loss reduction*

Basic relationship for calculating the total energy consumption of a manufacturing system. The energy consumed by an automated system can be divide into three main components:

$$E_{total} = E_{operation} + E_{idle} + E_{loss} \quad (2)$$

Where:

- $E_{operation}$ is Energy required for the production process.
- E_{idle} is standby consumption.
- E_{loss} are Energy losses due to inefficiency.

Each component can be optimized through system modernization or the introduction of renewable energy sources.

5 CASE STUDIES AND VISUALIZATIONS

Graph at Figure 1 compares energy consumption before and after optimization of production systems.

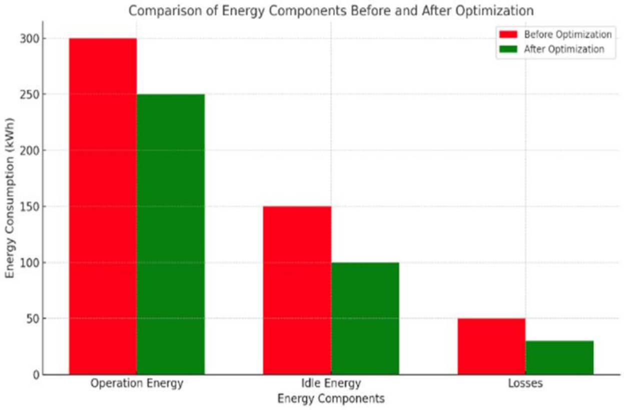

Figure 1. Graph comparing energy consumption before and after optimization of production systems

The optimization included measures such as reducing machine idle times, improving process efficiency, and upgrading auxiliary systems. The graph highlights the differences in energy consumption across three categories: Idle Energy, Processing Energy, and Auxiliary Energy.

5.1 *Energy consumption before and after optimization of CNC lines*

After implementing modern sensors and AI on CNC machines, the following results were achieved:

- Before optimization: 500 kWh/day.
- After optimization: 350 kWh/day.

5.2 *Efficiency trends*

Predicted adoption of AI and IoT in industrial systems is shown on graph at Figure 2 which compares industrial energy trends for the period 2024 to 2034 and the projected increase in AI adoption and energy efficiency percentages over time. The blue curve depicts the expected increase in artificial intelligence adoption, while the green shows improvements in energy efficiency.

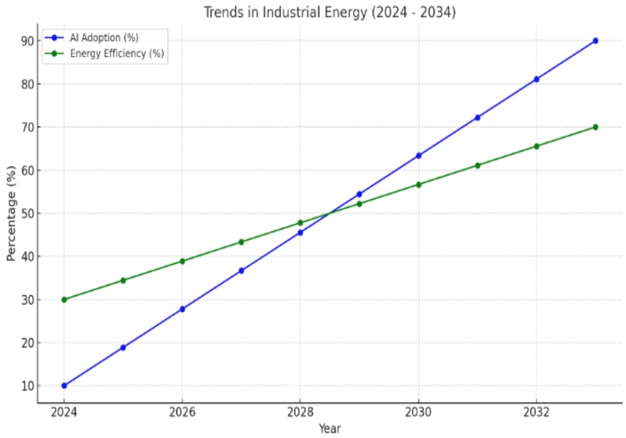

Figure 2. Trends in Industrial Energy (2024 to 2034)

6 INNOVATIONS – TECHNOLOGIES, STRATEGIES AND METHODS TO IMPROVE ENERGY EFFICIENCY

In the field of automated manufacturing systems, several technologies and strategies can significantly improve energy efficiency, as analyzed in the following subchapter.

6.1 *Advanced control and monitoring systems*

Advanced control systems (SCADA, PLC, and DCS) together with advanced algorithms allow monitoring and optimizing energy consumption in real time [Sapietova 2011]. These systems are used to monitor the performance of equipment and to analyse data from sensors, which allows for precise control of processes and equipment. For example, if it is identified that, a device is not operating in an optimal mode; the control system can adjust operating conditions or require intervention, thereby minimizing unnecessary energy consumption [Saga 2014].

Systems that use machine learning and artificial intelligence can predict energy consumption based on historical data and current production conditions. Predictive analytics can help prevent inefficient energy use due to equipment failure or undersized processes.

Example:

When a production facility reaches a set production level, the SCADA system can automatically adjust the motor speed or change the heating or cooling mode to minimize energy waste. Such control can significantly reduce overall energy consumption without negatively affecting production quality [Saga 2018].

6.2 Optimization of production processes

Automated manufacturing systems can benefit significantly from optimizing the manufacturing processes themselves. This may include:

• Production cycle optimization: Implementing technology that allows production processes to dynamical adapt to current conditions, such as production speed, temperature or humidity. This dynamic approach can reduce the time machines spend in inefficient operating modes, thereby saving energy [Holubcik 2012] .

• Integrating Lean Manufacturing methods: The concept of lean manufacturing focuses on minimizing waste, including energy waste, and optimizing production processes. Implementing these principles into automated manufacturing systems allows for the elimination of redundant processes and reduced energy consumption [Kuric 2021].

6.3 Use of renewable energy sources

Incorporating renewable energy sources, such as photovoltaic panels, wind turbines or biomass systems, is an effective way to reduce the consumption of conventional energy and minimize environmental impact. Renewable sources can be integrated into existing production processes to cover part of the energy requirements. Connecting these systems with advanced control and monitoring systems allows for their efficient use and optimization depending on the current energy needs [IEA 2022].

6.4 Efficient use of motors and inverters

One of the key technologies for improving energy efficiency is the use of energy-efficient motors and inverters. Modern motors are design to minimize energy losses and operate at optimized speeds. Inverters allow the motor power to be adjust to the current needs of the production process, which means that equipment is not running at full power when it is not need. This can lead to significant reductions in energy consumption without affecting the overall performance of the system [Klackova 2024].

6.5 IoT and sensors

IoT and sensors play a key role in monitoring and improving energy efficiency in automated manufacturing systems. IoT allows devices to communicate with each other and share information about operating conditions, which allows energy consumption to be optimize (Figure 3). Sensors that monitor parameters such as temperature, pressure, humidity or vibration allow problems to be detect before they become critical, reducing the risk of excessive energy loads [Klarak 2024].

Figure 3. Utilization of the industrial Internet of Things and automation

6.6 IoT and intelligent systems

IoT is revolutionizing energy management in industrial production systems. Sensors placed at various points along production lines allow real-time data collection on energy consumption and equipment performance. Based on this data, dynamic energy management can be implemented, production processes can be optimized, and waste can be reduced.

Example of IoT application in energy efficiency:

• Smart meters allow you to track energy consumption at the device level. This data can be used to analyse consumption trends and predict future energy consumption, leading to better management of the production process [Klackova 2021].

Example of a relationship for consumption prediction:

$$P_{before} = f\,(S,T,D) \qquad (3)$$

Where S is the equipment status, T is the cycle time and D is the production demand.

IoT sensors monitor real-world energy consumption and help with optimization.

6.7 Energy recovery – Recuperation systems

Energy recovery systems can significantly reduce losses.

Example: Industrial braking regenerates kinetic energy into electrical form:

$$E_{regen} = \tfrac{1}{2}\, m v^2 \times \eta_{regen} \qquad (4)$$

Where m is the mass of the object, v its speed, and ηregen is the recuperation efficiency.

Energy recovery systems (e.g., industrial brakes or thermal regeneration) can reduce losses by up to 30%. For instance, Energy Recovery's PX G1300 device has been shown to improve the efficiency of CO_2 refrigeration systems by up to 30% at higher temperatures [Energy Recovery, Inc. 2024].

Additionally, the U.S. Department of Energy notes that implementing heat recovery systems can lead to significant energy savings, with typical heat recovery rates around 30% [Chapman 2019].

These examples demonstrate the potential of energy recovery systems to substantially reduce energy losses in various industrial applications.

6.8 Work cycle optimization

- Shortening standby times.
- Dynamic production planning based on current demand.

6.9 Automatic control and monitoring

Using sensor networks and software tools to detect energy losses:

$$P_{\text{loss}} = P_{\text{input}} - P_{\text{useful}} \qquad (5)$$

Where P_{loss} is the energy loss, P_{input} is the total energy input, and P_{useful} is the useful work.

6.10 Predictive maintenance

Predictive maintenance is another technique that can improve energy efficiency. This approach uses sensor data and advanced algorithms to predict equipment failures and perform maintenance before a failure occurs [Klackova 2022]. Predictive maintenance can minimize unplanned downtime and reduce the need for inefficient equipment operation, which reduces energy consumption.

7 THE IMPORTANCE OF HUMAN FACTORS AND TRAINING

To achieve maximum energy efficiency in automated manufacturing systems, the human factor must also be taken into account. Technologies such as advanced control systems and IoT provide a wealth of data, but their correct interpretation and application depend on qualified professionals [Sagova 2022]. Regular training of employees and raising their awareness of the importance of energy efficiency is key to ensuring the correct use of new technologies and processes. Training employees to recognize energy losses and raising their awareness of the importance of energy conservation can contribute to improving the efficiency of the entire system. Even small changes, such as turning off equipment when not in use, can have a cumulative effect on overall energy consumption.

8 CHALLENGES, PERSPECTIVES AND FUTURE OF ENERGY EFFICIENCY

Industrial energy is moving towards full automation and minimization of energy losses. The main trends include:

- Integration of renewable energy sources (solar and wind systems).
- Expanding the use of digital twins for manufacturing simulation and optimization.
- Intelligent control systems with advanced data analysis.

Despite advanced technologies and innovations in energy efficiency, the industry faces several challenges:

- High initial costs for implementing advanced control systems, sensors and renewable energy sources.
- The complexity of integrating new technologies into existing production lines, which may require extensive reconstruction and process adaptation.
- Regulatory and political factors that may affect investments in energy innovation.

Solutions for the future:

In the future, we can expect a faster development of smart manufacturing systems that will use energy even more efficiently and will be closely integrate with renewable energy sources. With the gradual development of technologies in the field of AI and IoT, new possibilities for reducing energy demands are opening up [Thiede 2012].

CONCLUSIONS

Improving the energy efficiency of AMS has direct economic and environmental benefits. Future trends include:

- Greater integration of artificial intelligence and IoT into control systems.
- Transition to renewable energy sources in production.
- Advanced data analysis methods for consumption and maintenance prediction.

By properly designing and optimizing automated production systems, it is possible to achieve high levels of efficiency, thereby ensuring the competitiveness of enterprises in the global market. By properly designing and optimizing automated production systems, it is possible to achieve high levels of efficiency, thus ensuring the competitiveness of enterprises in the global market. Energy efficiency in automated production systems represents a complex challenge that requires the integration of various technologies, such as advanced control and monitoring systems, renewable energy sources, predictive maintenance and optimization of production processes. The combination of these approaches can significantly reduce energy consumption, minimize costs, and at the same time contribute to environmental sustainability. To successful achieve these goals, it is essential that enterprises implement integrated solutions and regularly train their employees in the proper management of energy resources.

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