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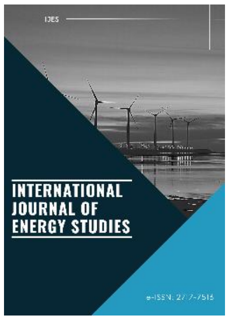

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Energy efficiency analysis with data obtained from aluminum melting factory

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Highlights

- The impact of Industry 4.0 on energy efficiency
- The high proportion of aluminum production within the total cost is noteworthy.
- The Internet of Things (IoT)

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ABSTRACT

In the Industry 4.0 revolution, which first emerged in Germany, the primary goal has been to increase production efficiency using Internet of Things (IoT) technology. Industry 4.0 is positioned to serve as a bridge in the triangle of people, processes, and technology. Here, the human is referred to as the user, the process as the organizational structure, and technology as software and hardware. The "Automation Pyramid," which has come to the forefront with Industry 4.0, has been defined as the general framework for establishing these bridges. With the increased product variety brought by Industry 4.0, the energy consumed in production facilities has also started to show upward variability. At the same time, rising unit energy costs have encouraged factories to work on energy efficiency. Industry 4.0 aims to digitize factories. With this digitalization, data (production data, energy data) is collected from the production site independently of human statements. The data obtained not only guide factory improvement efforts but also enable the creation of plans for the efficient use of energy in production work orders. In this study, the change over the years in the impact of improvement efforts on energy efficiency in a factory where data was collected from the production site has been evaluated.

Keywords: Sustainable policy, Energy transition, Energy efficiency, Industry 4.0, Internet of Things (IoT)

1. INTRODUCTION

Industry 4.0 has transformed the foundation of existing industrial processes, making production systems smarter, more flexible, and more efficient through the integration of technology and automation. In this context, the effective management of energy use in industrial sectors is crucial for both sustainability and competitive advantage. This study aims to examine the impact of Industry 4.0 on energy efficiency by focusing specifically on the analysis of energy efficiency in aluminum smelting plants.

The Industry 4.0 paradigm, introduced at the Hannover Fair in Germany in 2011 and subsequently declared by the Federal German Government as industrial modernization, has indicated significant changes that will profoundly affect all sectors in the future. This transformation has led to fundamental changes in the structure of the labor market and has brought technological advancements, such as dark factories, the Internet of Things, and augmented reality—concepts that humanity had not previously encountered [1]. The fundamental changes anticipated by Industry 4.0 refer to rapid transformations across all processes, starting from the design of production processes, through the production phase, operation, and service. This means a system that is more flexible, demand-oriented, and open to predictable changes compared to traditional production models [2]. The economic impacts of Industry 4.0 have caused tangible changes in a range of areas, from production processes to the labor market and working conditions. This model, in which production has shifted from being mass-oriented to a more flexible and demand-centered structure, represents a paradigm different from previous Taylorist approaches, where labor organization has transformed into a more flexible form [3]. In order to fully understand Industry 4.0, it is necessary to comprehend the fundamental terms and concepts related to the system. The use of applications related to these fundamental components today carries important clues for the future developments of Industry 4.0. Especially technologies that have become indispensable parts of our lives, such as the Internet of Things and 3D printers, are clear indicators of these advancements [4]. The term "IoT," known as "Internet of Things," refers to a system called "Nesnelerin İnterneti" in Turkish, which allows real-world objects to communicate through sensors (Banger, 2016: 186). This concept, which began with the use of cameras placed in a coffee machine in 1991, became even more popular with the Internet of Things concept proposed by Kevin Ashton in 1999 [5].

The concept of "Big Data" refers to the entirety of data obtained over a specific period that has not yet been organized or processed using any traditional methods or tools. These extensive data sets have become an important topic today with the rapid advancement of technology and the widespread use of the internet. These data are accumulating in large amounts every day through telephone operators, social media posts, online correspondence, and other platforms. However, within this data heap, there may also be misleading or criminal information alongside accurate data. Big Data has gained importance as a tool used to extract accurate and meaningful information from this data chaos [7].

Cloud computing and Internet of Things (IoT) technologies have greatly facilitated the processing and storage of Big Data. These technologies enable the rapid transmission and storage of data through internet-based infrastructures. Especially, cloud computing can easily perform computations that require large hardware and provides a wide area for data storage. The Internet of Things, on the other hand, enables data sharing and communication between physical objects. These technologies enable the effective use of Big Data [8]. 3D printers, also known as three-dimensional printers, are quite impressive machines that can convert three-dimensional data from the digital world into physical objects. Their ability to produce almost all mechanical components except for motors and electronic parts makes 3D printers versatile and useful. These printers can perform printing operations using different methods and techniques. Basically, the working principle of 3D printers is that an object designed through computers is virtually divided into layers, and each layer is physically printed by layer by layer combining melted material. Cyber-physical systems is a term that describes systems where computer technologies are integrated with physical components and possess an interdisciplinary characteristic, while also being significantly complex. Therefore, cyber-physical systems are those that can coordinate and harmonize production processes, logistics processes, and other supply chain operations at the highest level. These systems, which can perform tasks that are nearly impossible with human power and intelligence in real-time, can optimize and manage operations at high performance levels [10]. This hybrid technology makes physical machines smarter by integrating them with cyber technology. In this context, the process is defined as cyber-physical systems as a whole [11]. For example, comforts such as the car's air conditioning starting to work before the driver wakes up or the windshield wipers automatically activating when raindrops fall on the windows during driving can be cited as examples of the advantages provided by cyber-physical systems [12]. With the fourth industrial revolution, the need for embedded systems capable of producing more software and advanced algorithms will increasingly grow. Self-managing, decision-making, and communicative systems form the foundation of the Industry 4.0 revolution [13].

Within the scope of this study, the measurement and analysis of the increase in energy efficiency achieved through the implementation of Industry 4.0 have been carried out using real data obtained from an aluminum smelting factory. The research is designed to understand the impact of the digitalization and automation of industrial processes on energy consumption, fill the gaps in the existing literature, and contribute to sustainable production practices in the aluminum melting sector.

The conducted study has revealed the potential of Industry 4.0 in the field of energy efficiency and provided practical information regarding its applications in aluminum smelting plants. The results of the research are expected to be valuable for researchers, industry professionals, and decision-makers who aim to develop energy management strategies in the industrial sector.

2. ENERGY EFFICIENCY AND TURKIYE

Energy efficiency is an important issue today, aiming to minimize energy losses by using diminishing energy resources more effectively. This aims to reduce energy consumption without compromising waste recovery and product quality. The primary goal of energy efficiency is to use limited energy resources to the least extent. According to this understanding, energy efficiency establishes a balance between the saved energy and the expenses contributing to this saving. In this context, it is necessary to address the negative factors affecting energy efficiency and to use development methods and advanced technologies to enhance energy efficiency [21]. Energy audit studies conducted in industrial enterprises show that there is energy-saving potential in most businesses. These studies demonstrate that energy savings are possible even with the use of no-investment or low-cost applications [22]. Businesses can use energy more effectively by increasing energy audit studies and implementing applications with energy-saving potential. Additionally, raising employee awareness about energy efficiency and ensuring the sustainability of these efforts will provide long-term environmental and economic benefits. Therefore, energy efficiency can contribute not only to cost savings for businesses but also to achieving environmental sustainability and competitive advantage. In our country, energy efficiency is at a lower level compared to other countries. However, the integration of developing technologies into old systems and energy efficiency-focused efforts can enhance performance in this area. It is believed that energy efficiency efforts will contribute to the national economy by reducing energy costs and strengthen the sector's competitive power. The first steps taken in our country regarding energy efficiency were initiated with two regulations published in the Official Gazette on 19.9.1972 and 3.11.1972. However, the lack of sufficient binding force in these regulations has hindered achieving the desired level of efficiency [23]. Our country has taken strategic steps towards energy efficiency by being a party to the United Nations Framework Convention on Climate Change (2004) and the Kyoto Protocol (2009). Energy efficiency has also been addressed as an important issue in our country's 7th and 8th Five-Year Development Plans. The 7th Five-Year Development Plan has stated the goal of using energy resources more efficiently by reducing energy intensity, increasing efficiency, and implementing conservation programs [24]. With the development of our industry and the increase in our population, our energy consumption has shown a continuous upward trend over the years. In order for our country to maintain a strong position in the global competition arena, it needs to pay attention to energy consumption and carry out its current energy programs more effectively. Especially in recent years, the 14% increase in energy consumption has become more pronounced compared to previous years, and this situation is quite noteworthy in terms of energy management. Among developing countries, Turkey is showing a trend of increasing energy consumption. Annual energy consumption is increasing at a rate above the world average, and this situation indicates that our country's energy demand is rising rapidly [25-26]. The rapid growth of energy demand in our developing country, with its limited energy resources, increasing population, and industry, makes the issue of energy efficiency even more important [27]. The high proportion of aluminum production within the total cost is noteworthy. The implementation of energy efficiency in these sectors can lead to significant reductions in unit costs, and this situation can enhance the competitiveness of our country's aluminum sector [28-29].

3. A LOOK AT INDUSTRY 4.0 AND ENERGY EFFICIENCY: ENERGY EFFICIENCY ANALYSIS WITH DATA OBTAINED FROM AN ALUMINUM SMELTING PLANT

3.1. Automation Pyramid in Industrial Enterprises

The industrial automation pyramid, as shown in Figure 1, is a model that hierarchically represents the automation systems found in a manufacturing facility. The base of the pyramid consists of field-level devices that control the physical processes of the facility. At the top of the pyramid, there are management-level systems used to monitor and control the overall performance of the facility.

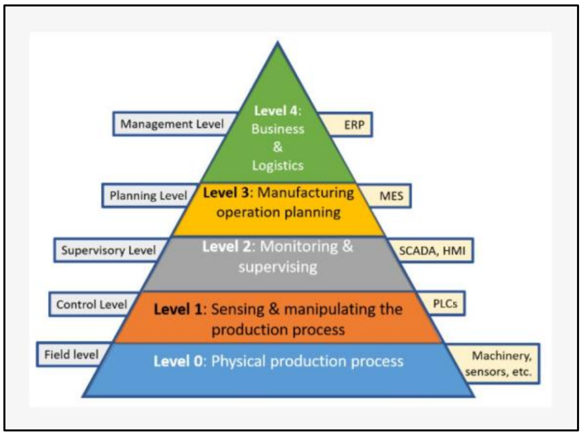


Figure 1. Industrial Automation Pyramid

3.1.1. Level 0: Field Level

The field level consists of sensors, actuators, and controllers that control machines, equipment, and processes. Sensors collect data from the environment, and actuators control machines and equipment based on this data. Controllers process the data from the sensors and generate commands to send to the actuators. Field-level automation systems generally consist of various components, including the following:

- Sensors: collect data from the environment
- Actuators: control machines and equipment
- Controllers: process data from sensors and send commands to actuators

Field-level automation systems play an important role in increasing the efficiency and productivity of industrial enterprises. These systems help ensure that machines and equipment operate more efficiently, reduce errors, and improve production quality

3.1.2. Level 1: Control Level

Programmable Logic Controllers (PLC) are effective control devices located at the middle level of the industrial automation pyramid. These devices are programmable logic control systems used to manage, monitor, and optimize production processes. These systems play an important role as one of the cornerstones of industrial automation. PLCs are used in various applications in the industry due to their capacity to perform complex logic controls. They function effectively, especially in areas such as machine and equipment control, process control, safety controls, data collection, and analysis. These control devices are a turning point in the evolution of industrial automation. They enable production processes to become more efficient, safe, and consistent.

PLCs contribute to making industrial facilities smarter, more flexible, and more competitive with the development of automation. Additionally, with continuous technological advancements, the capabilities of PLCs are constantly increasing and they continue to play a significant role in the future of industrial automation.

3.1.3. Level 2: First Tier Management Level

Positioned on the third layer of the industrial automation pyramid, SCADA (Supervisory Control and Data Acquisition) systems play a key role in monitoring and controlling industrial processes. These systems continuously collect data from various devices in the field and gather this data at a central point, enabling the effective management of industrial facilities. At this point, it is important to note that SCADA systems are a fundamental component that adapts to contemporary industrial trends such as Industry 4.0 and smart factories. SCADA systems are built on two main components: software and hardware. SCADA software enables the effective management of industrial processes by providing functions such as data collection, analysis, alarm management, and reporting. On the other hand, SCADA hardware performs data collection and transmission processes by running this software. The harmony between these two components ensures that SCADA systems operate robustly, reliably, and quickly. The functionality of SCADA systems focuses on fundamental elements such as data collection from field devices, data analysis, alarm management, and reporting. Thanks to data collection from field devices, the real-time status of industrial processes can be monitored and interventions can be made when necessary. Data analysis enables the in-depth examination of the collected data, allowing for the early detection of potential issues in the processes. Alarm management enables the rapid identification of abnormal conditions and their communication to operators, which is critically important for workplace safety. Reporting, on the other hand, ensures that process performance is regularly monitored and improvements are made when necessary. SCADA systems are an indispensable part of industrial automation and hold a significant place in today's industrial landscape. These systems, extending from the field to a central control point, offer significant advantages in addition to increasing efficiency, such as reducing costs and ensuring workplace safety. Therefore, in terms of effectively managing and optimizing industrial processes, the demand for SCADA systems is showing an increasingly upward trend.

3.1.3. Level 3: Management Level

The Manufacturing Execution System (MES), located at the management level of the industrial automation pyramid, offers various important functions to manage production processes more efficiently and optimize operational performance.The key functions provided by MES in the context of industrial automation are as follows:

1. Production Planning and Management:
    - Resource Allocation and Control: Automatic allocation and control of equipment, labor, and other resources.
    - Production Shipment: Management of the automated production flow and its appropriate dispatch to the equipment.
2. Data Management:
    - Data Collection and Integration: The collection and integration of production data through automatic sensors and systems.
    - Quality Management: Monitoring and regulating production quality through automatic quality control systems.
3. Business Processes and Performance Improvement:
    - Process Management: Optimization of operational processes through automatic process monitoring and correction mechanisms.
    - Production Tracking: Automatic production status monitoring and management of job completion stages.
4. Resource Management:
    - Operations and Detailed Scheduling: Programming of production operations and automatic processing according to the specified schedules.
    - Document Control: Automatic control and regulation of production-related documents.
5. Infrastructure Management:
    - Workforce Management: Automated tracking and reporting to increase personnel productivity.
    - Maintenance Management: Automatic maintenance tracking and continuous monitoring of equipment status.
    - Transportation, Storage, and Tracking of Materials: Automatic monitoring of material management and transfer processes.

The comprehensive functions of MES enable production facilities to operate in an automated and optimized environment. This can lead to significant reductions in production costs, energy consumption, and cycle time, enhancing the competitive advantage provided by industrial automation. MESA (Manufacturing Enterprise Solutions Association) aimed to provide meaningful data on the real benefits of MES to manufacturing and finance managers through two survey analyses conducted with its members from different sectors in 1993 and 1996. According to the results of these analyses, the use of MES can reduce production cycle time by 40%, data entry time by 55%, work in progress by 25%, delivery time by 27%, product defects by 19%, and the amount of paperwork between average shifts by 56%. Facilities using MES have experienced a 34% reduction in production costs, a 57% reduction in energy consumption, and a 37% reduction in cycle time compared to those not using MES [30].

3.1.4. Level 4: Corporate Level

Organizations today implement various methods to gain a competitive advantage, increase their efficiency, and optimize their processes in complex and dynamic business environments. In this context, Enterprise Resource Planning (ERP) software stands out as comprehensive software systems aimed at integrating and effectively managing various business processes. ERP systems have a modular structure that integrates and enables interaction between different business processes in areas such as finance, human resources, production, supply chain management, sales, and marketing within a company. This integration increases information sharing between departments and ensures the consistency of processes. Core modules such as financial management, human resources management, production, and supply chain management ensure the effective management of business processes.

4. INDUSTRIAL BUSINESS INFORMATION

4.2. General Information About The Business

Established in Istanbul and starting its operations in the mold manufacturing field, the business began to take part in the casting sector in the following years. has started. To meet the increasing demands, the business expanded its factory building and, starting from 2006, integrated its facility with the infrastructure capable of meeting all the requirements of the metal injection sector. has been integrated. In the organization, which has advanced engineering capabilities and possibilities to meet the needs of the entire main industry, services are provided to many different sectors such as automotive, energy, lighting, and construction provides services [31-

32]. As of 2021, in addition to the existing Enterprise Resource Planning (ERP) software, it has started collecting data from a total of 48 points for electricity, including 18 metal injection machines, 18 mold heaters, 8 electric holding furnaces, 1 annealing unit, and 3 compressors, and from a total of 18 points for natural gas, including 5 main melting furnaces, 3 preheating units, and 10 natural gas holding furnaces, using the Manufacturing Execution System (MES). In addition to energy data, the organization that collects and analyzes basic production data such as production, scrap, and downtime through MES software has increased its efforts to improve production efficiency based on the obtained information day by day. Stating that these digital data improve decision-making processes, the organization expresses its aim to increase efficiency day by day.

4.3. Business Production Process

In the organization, aluminum part casting is generally carried out. The process followed after the entry of the raw material (aluminum ingot) into the facility is carried out in the order specified below.

1. Raw Material Storage
2. Melting, Gas Extraction
3. Al Injection
4. Trimming
5. CNC Machining (for necessary parts)
6. Deburring with Vibration and Washing with Rinsing
7. Final Control
8. Shipment

4.4. Temperature Measurements in Various Panels in the Facility

In the inspection of the external transformer building and the internal electrical panels of them factory, mostly renovated structures were encountered. It has been observed that the selected busbar and cable cross-sections were installed in anticipation of a possible future capacity increase for the factory. No unwanted loss or leakage of power due to overcurrent or overheating has been detected inside the panels. It has been observed that the internal temperatures of the panel are in the range of 20-30 degrees, and the temperatures of the busbar and cables do not exceed 35 degrees. This situation is considered one of the important steps the organization has taken in terms of using energy efficiently in production. Figure 2 exhibits the temperature measurements on various panels.

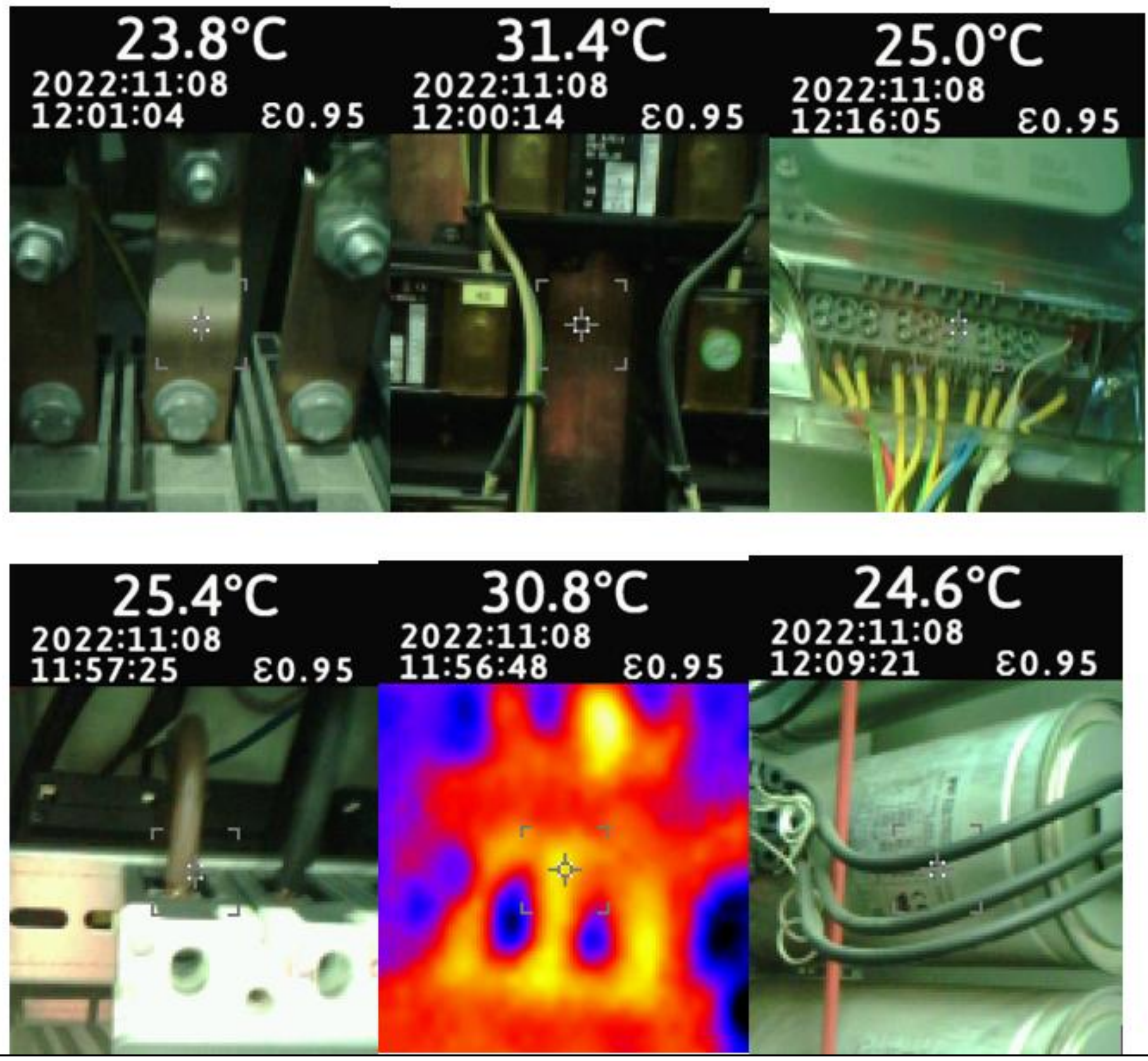


Figure 2. Temperature measurements on various panels

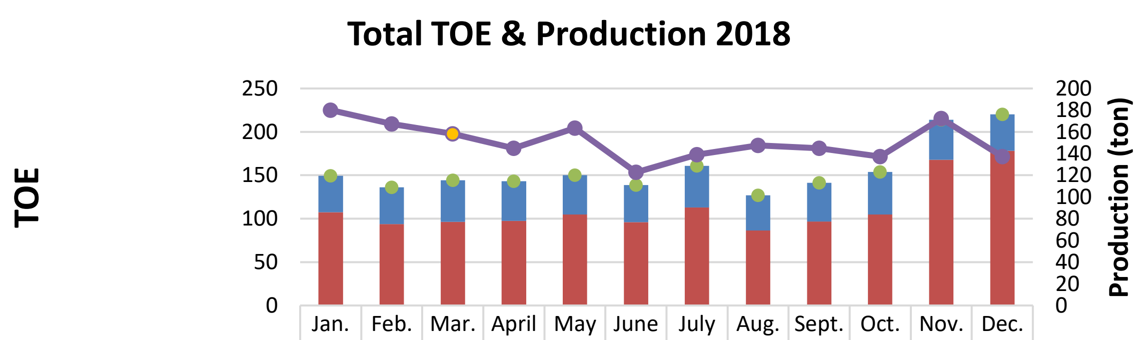
5. INDUSTRIAL BUSINESS DATA ANALYSIS

In this study, the energy consumption and production values of the last 5 years (2018-2022) of the business were analyzed. The total amount of melted Aluminum (Al) has been accepted as the production. Two different types of energy sources have been used in the facility, namely electricity and natural gas. The changes in production and energy consumption every month from 2018 to 2022 have been shown with graphs.

In addition to historical energy and production data, the study includes detailed analysis of real-time data collected from the factory after the implementation of a Manufacturing Execution System (MES) in 2021. This system was integrated into the facility's infrastructure to enhance data acquisition and operational monitoring. Energy consumption data were collected from a total of 66 critical measurement points: 48 for electricity (including 18 metal injection machines, 18 mold heaters, 8 electric holding furnaces, 1 annealing unit, and 3 compressors) and 18 for natural gas (including 5 main melting furnaces, 3 preheating units, and 10 natural gas holding furnaces). The MES also enabled the collection of production-related data such as output, scrap rates, and machine downtimes. With this integrated digital infrastructure, monthly energy efficiency metrics (e.g., kWh/ton, m^3/ton) were calculated and compared across different time periods to assess the impact of Industry 4.0 applications. This dual-layered approach—combining historical trend analysis with real-time smart data—strengthens the study's findings regarding the role of digitalization in improving energy performance in aluminum smelting operations.

5.1. Examination of Total Energy Consumption and Total Production

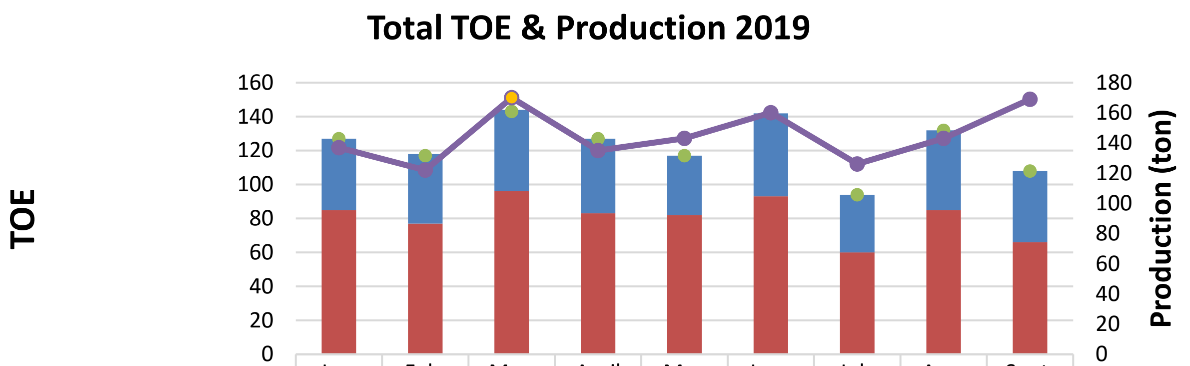
Figure 3 exhibits the monthly changes in production and energy consumption for the year 2018 are shown. In the facility, a total of 1,815.27 tons of Al were produced in 2018, and against this production, 1,879.12 TOE (Tons of Oil Equivalent) of energy was consumed. When evaluating the consumption rates, 28.6% of the total energy consumed is electricity, and 71.4% is natural gas energy. In 2018, the highest monthly production at the facility was 180 tons of Al in January, while the highest energy consumption was 220 TOE in December. The lowest monthly production occurred in June with 123 tons of Al, while the lowest consumption was in August with 127 TOE.



	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Electric Energy	42	42	48	46	45	43	48	41	45	49	46	42
Natural Gas Energy	107	94	96	97	105	96	113	86	97	105	168	178
Total TOE	149	136	144	143	150	139	161	127	141	154	214	220
SET-Based Production	180	167	158	145	163	123	139	148	145	137	172	137

Figure 3. 2018 Energy Consumption and Total Production Graph

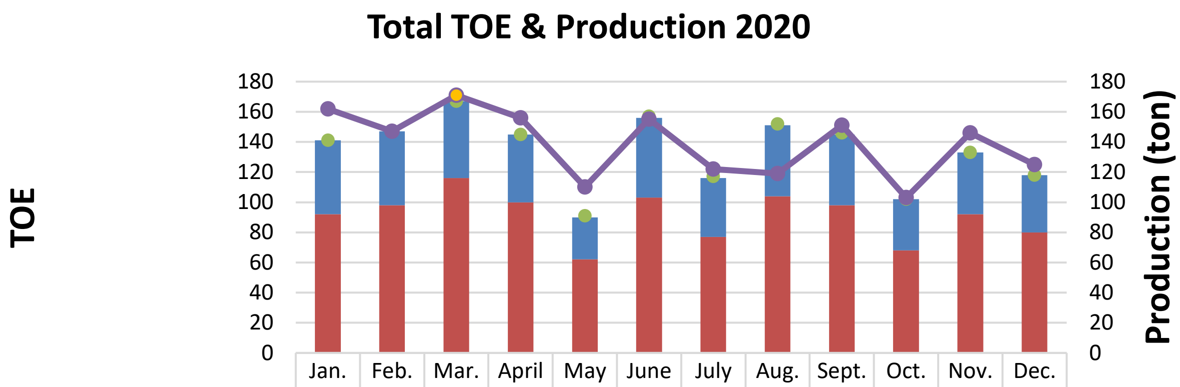
Figure 4 shows, when examining the monthly changes in production and energy consumption for the year 2019, a total production of 1,304.76 tons of Al was achieved, with an energy consumption of 1,107.22 TOE. It is observed that 34.3% of the total energy consumed was electricity and 65.7% was natural gas energy; the highest monthly production was 170 tons of Al in March, the highest energy consumption was also in March with 143 TOE, the lowest production was 122 tons of Al in February, and the lowest consumption was in October with 94 TOE.



	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.
Electric Energy	42	41	48	44	35	49	34	47	42
Natural Gas Energy	85	77	96	83	82	93	60	85	66
Total TOE	127	117	143	127	117	142	94	132	108
SET-Based Production	137	122	170	135	143	160	126	143	169

Figure 4. 2019 Energy Consumption and Total Production Graph

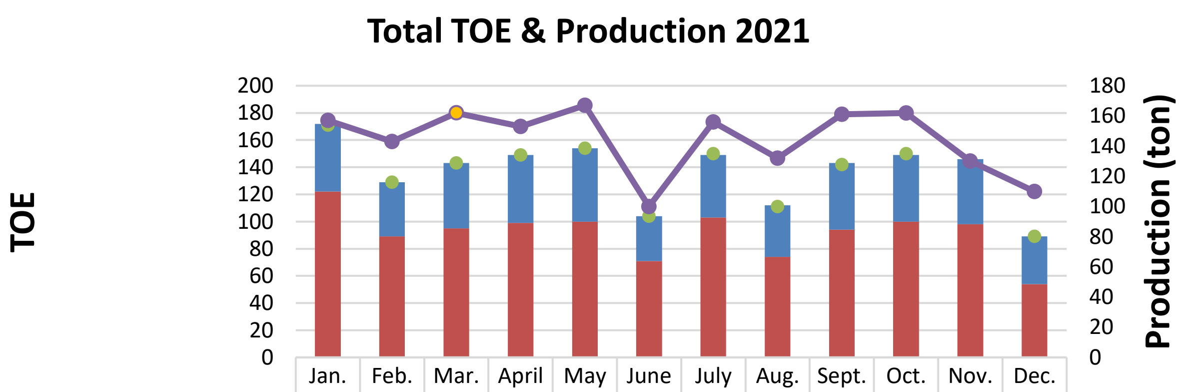
When examining the monthly production and energy consumption changes for the year 2020 in Figure 5 exhibits the observed that production was realized with a total of 1,667.85 tons of Al, while 1,614.90 TOE of energy was consumed. It is observed that 32.4% of the total energy consumed was electricity and 67.6% was natural gas; the highest monthly production was 171 tons of Al in March, the highest energy consumption was also in March at 167 TOE, and the lowest production was 103 tons of Al in October, while the lowest consumption was 91 TOE in May.



	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Electric Energy	49	49	51	45	28	53	39	47	47	34	41	38
Natural Gas Energy	92	98	116	100	62	103	77	104	98	68	92	80
Total TOE	141	147	167	145	91	157	117	152	146	102	133	118
SET-Based Production	162	147	171	156	110	155	122	119	151	103	146	125

Figure 5. 2020 Energy Consumption and Total Production Graph

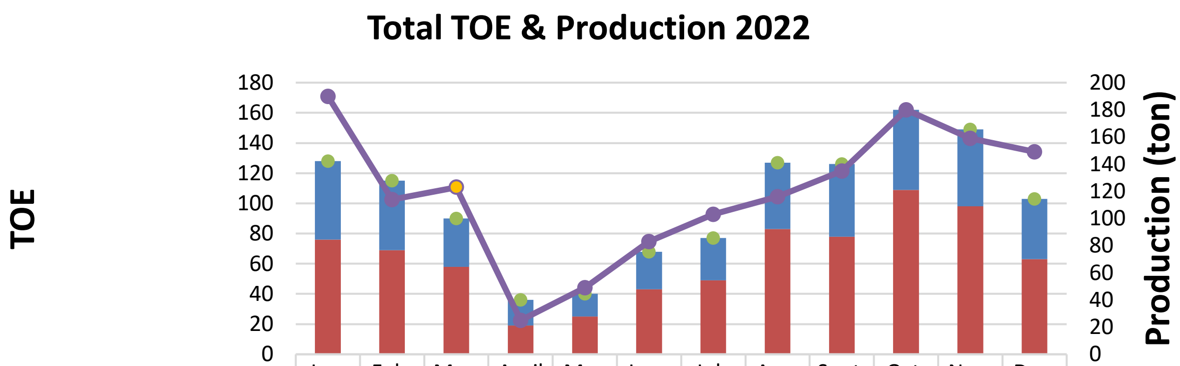
When examining the monthly changes in production and energy consumption for the year 2021, a total production of 1,733.57 tons of Al was achieved, with an energy consumption of 1,636.65 TOE is exhibited in Figure 6. It is observed that 32.8% of the total energy consumed was electricity and 67.2% was natural gas energy; the highest monthly production was 167 tons of Al in May, the highest energy consumption was 171 TOE in January, the lowest production was 100 tons of Al in June, and the lowest consumption was 89 TOE in December



	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Electric Energy	50	40	48	50	54	33	46	38	49	49	48	35
Natural Gas Energy	122	89	95	99	100	71	103	74	94	100	98	54
Total TOE	171	129	143	149	154	104	150	111	142	150	145	89
SET-Based Production	157	143	162	153	167	100	156	132	161	162	130	110

Figure 6. 2021 Energy Consumption and Total Production Graph

Figure 7 shows, when examining the monthly changes in production and energy consumption for the year 2022, production was realized with a total of 1,424.46 tons of Al, while 1,222.33 TOE of energy was consumed. It is observed that 37.1% of the total energy consumed was electricity and 62.9% was natural gas energy; the highest monthly production was 190 tons of Al in January, the highest energy consumption was 162 TOE in October, and the lowest production was 25 tons of Al in April, while the lowest consumption was also in April at 36 TOE.



	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Electric Energy	52	46	32	17	15	25	28	44	48	53	51	40
Natural Gas Energy	76	69	58	19	25	43	49	83	78	109	98	63
Total TOE	128	115	90	36	40	68	77	127	126	162	149	103
SET-Based Production	190	114	123	25	49	83	103	116	135	180	159	149

Figure 7. 2022 Energy Consumption and Total Production Graph

5.2. Regression Analysis of Production Quantity and Energy Consumption

In this section of the research, the relationships between production values (tons) and energy consumption (TOE) values from 2018 to 2022 have been evaluated. Regression analyses were conducted between the production quantity and the total energy consumed, as well as the amounts of energy types (Electricity, Natural Gas). The connection between production quantity and energy consumption is examined through regression analysis. The target for ideal energy management systems is for the regression coefficient to be above 0.75 and close to 1. In addition to total energy consumption, separate regression graphs were evaluated for electricity and natural gas energy types. All analyses were conducted based on the values from 2018-2022.

It is observed that there is a weak relationship between the production amount and the total energy consumed in 2018 (y=0.1295z+137, R2=0.006) as shown in Figure 8.

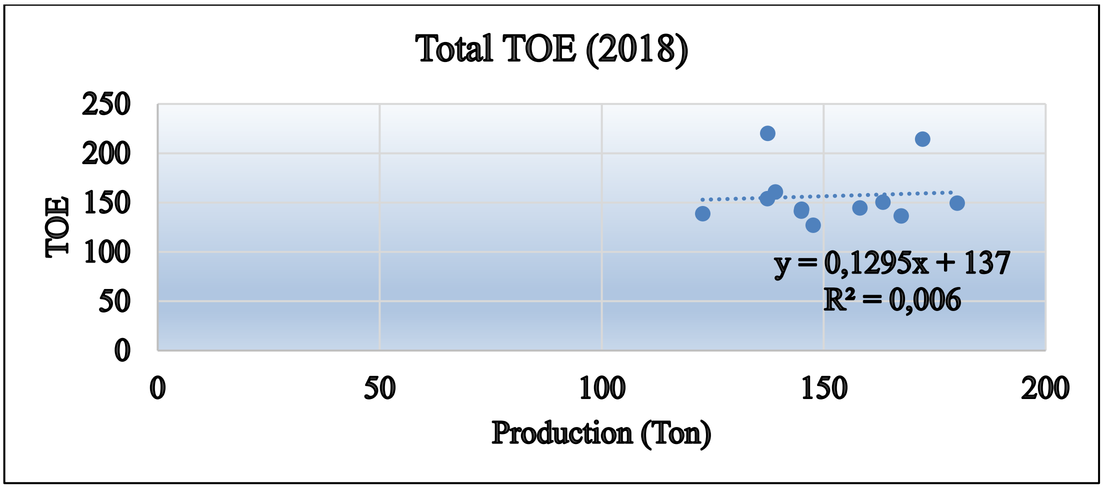


Figure 8. 2018 Production – Total Energy Consumption Trend Graph (Total)

Figure 9 shows that in 2019, there is a weak relationship between the production amount and the total energy consumed (y=0.4219x+61.86, R2=0.221).

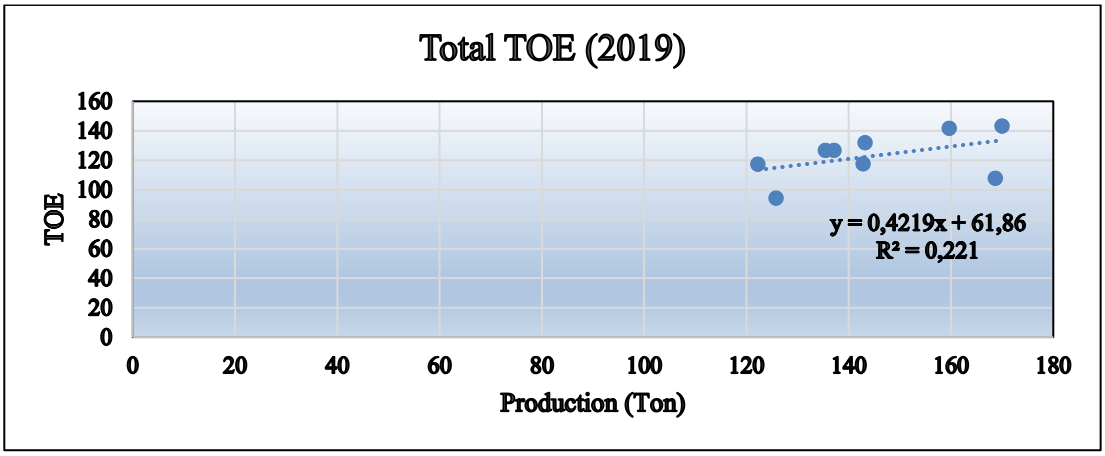


Figure 9. 2019 Production – Total Energy Consumption Trend Graph (Total)

It is observed that there is a strong relationship between the production quantity and the total energy consumed in 2020 (y=0.8505x+16.371, R2=0.669) shown in Figure 10.

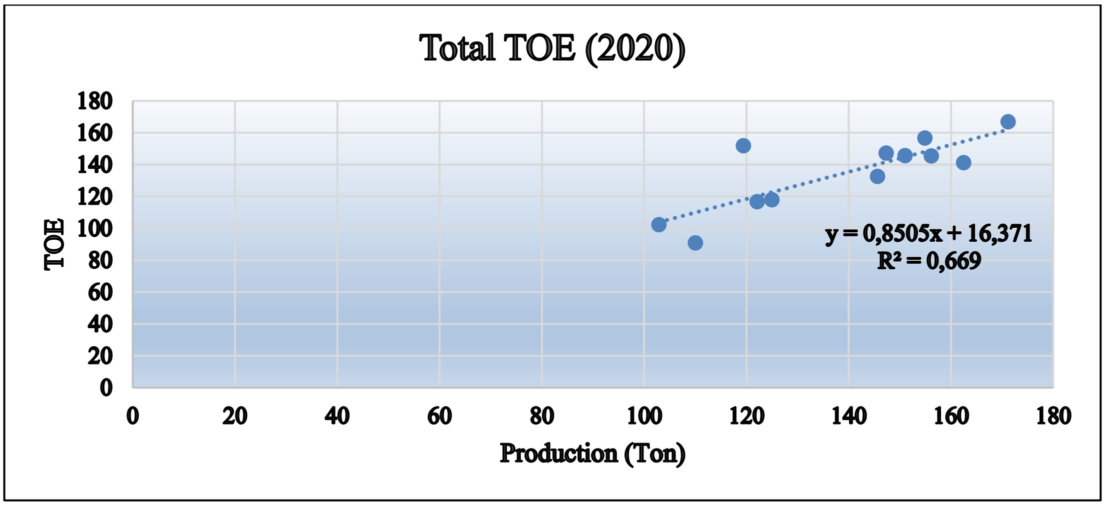


Figure 10. 2020 Production – Total Energy Consumption Trend Graph (Total)

Figure 11 exhibits a strong relationship is observed between the production quantity and the total energy consumed in 2021 (y=0.9112x+14.7506, R2=0.711).

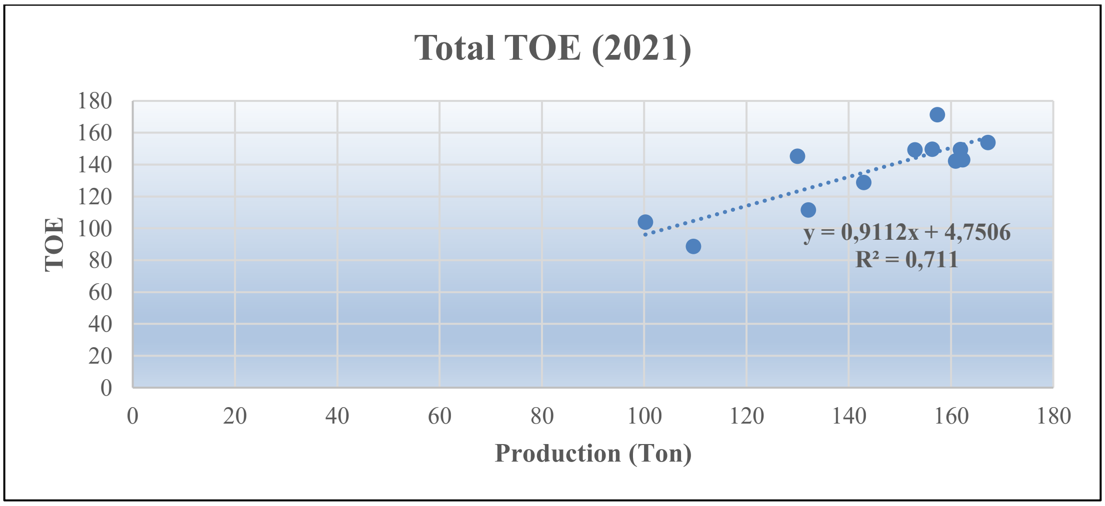


Figure 11. 2021 Production – Total Energy Consumption Trend Graph (Total)

It is observed that there is a strong relationship between the production quantity and the total energy consumed in 2022 (y=0.7349x+14.63, R2=0.811) shown in Figure 12.

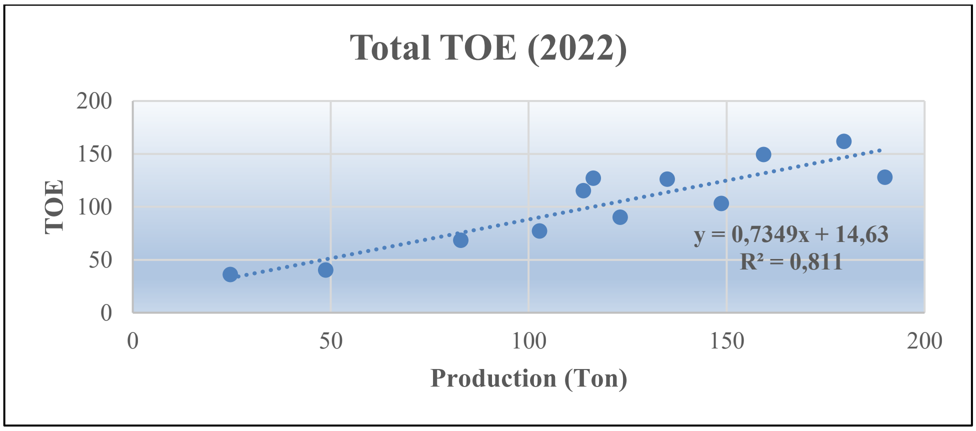


Figure 12. 2022 Production – Total Energy Consumption Trend Graph (Total)

The change in the regression rates between the production amount and the energy consumed from 2018 to 2022 is shown in Figure 13.

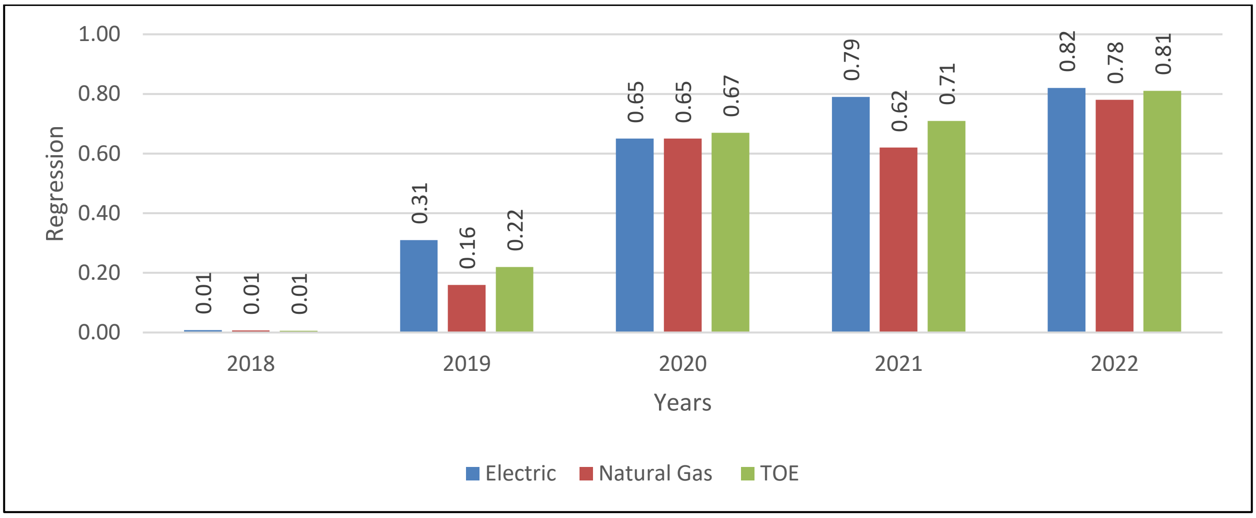


Figure 13. Change in Production – Energy Consumption Regression Rates for the Years 2018-2022

5.3. Quality Review

The industrial enterprise, in 2021, at the Management Level stage of the industrial automation pyramid, began to collect quality data related to the products produced with the implementation of the Manufacturing Execution System (MES). The quality rate calculated using the total number of sound parts obtained and the total number of parts produced provides an important output for continuity in quality processes. With quality data, the business has gained a significant advantage by analyzing historical data to prevent the recurrence of quality errors and ensure continuity in quality.

In Figure 14, the monthly changes in the quality data obtained from data collection points in the years 2021 and 2022 have been examined. The average quality rate in 2021 was 97.3%, while this rate was calculated as 97.1% in 2022. In 2021, the highest quality rate was observed in May at 97.7%, while in 2022, the highest quality rate was observed in April, May, and October at 97.4%. When evaluating the quality change in the first 6-month period of 2021-2022, the quality rate in the first 6-month period of 2021 was 97.6%, and in the first 6-month period of 2022, the quality rate was 97.1%; while the quality rate in the second 6-month period of 2021 was 96.9%, in the second 6-month period of 2022, the quality rate was 97.1%. As a result, the quality rates in 2021 and 2022 have remained quite high on a monthly and annual basis.

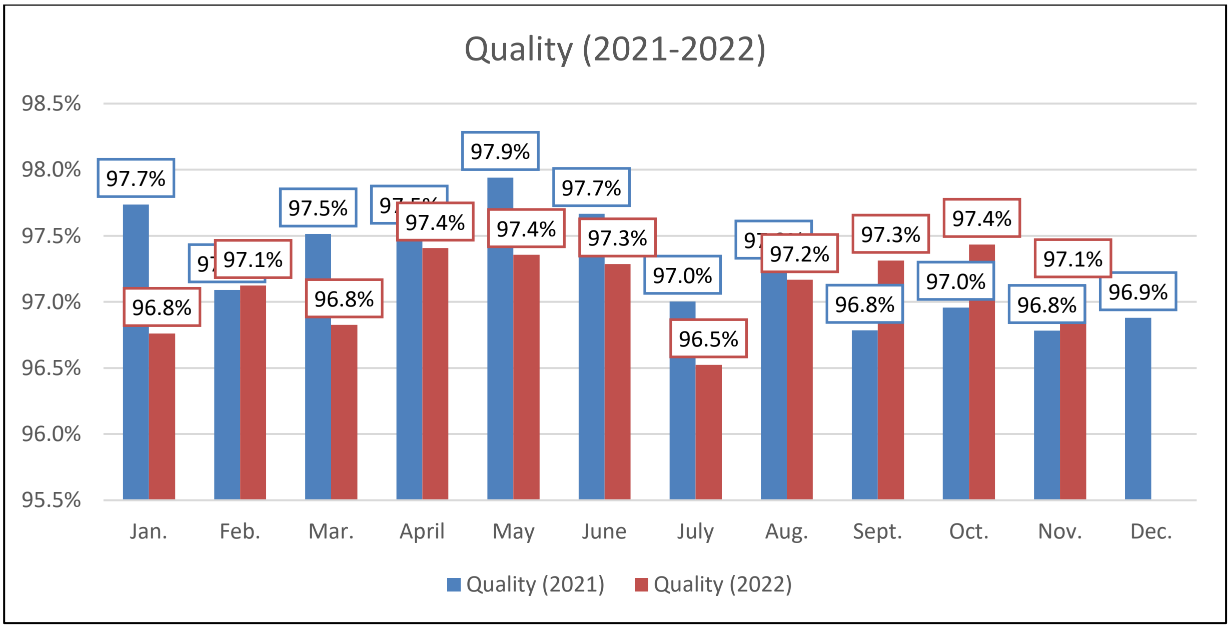


Figure 14. Quality Change Rates Between 2021 and 2022

6. CONCLUSION

Industry 4.0 refers to a transformation that aims to increase efficiency in production by integrating traditional manufacturing processes with digital technologies. This approach involves the use of innovative technologies such as automation, data analysis, artificial intelligence, and the Internet of Things (IoT). The applications of Industry 4.0 in the energy sector play an important role in increasing energy efficiency and creating a sustainable energy future. Energy efficiency means using resources more effectively and reducing energy consumption [33-34]. Industry 4.0 enables the optimization of energy consumption in production facilities through the use of smart sensors, automation, and data analysis. Thanks to the ability to communicate between production equipment, systems can be managed more precisely, and energy waste can be minimized [35-36].

With this study, the evaluation of an exemplary factory in terms of Industry 4.0 and energy efficiency has been conducted using the obtained data. As of 2021, the Sample Factory has integrated MES software into its existing ERP software, collecting electrical data from a total of 48 points, including 18 metal injection machines, 18 mold heaters, 8 electric holding furnaces, 1 heat treatment unit, and 3 compressors. Additionally, it has started collecting natural gas data from a total of 18 points, including 5 main melting furnaces, 3 preheating units, and 10 natural gas holding furnaces. The organization that enables the collection of data digitally from the source without human input through the MES system collects this data in real-time and can access it at any moment. In this way, it has aimed for continuity in quality by analyzing historical records. When looking at the quality rates calculated from the total number of sound parts and the total number of parts produced in 2021 and 2022, the average quality rate for 2021 was 97.3%, while this rate was measured at 97.1% in 2022. With this result, it has been observed that the organization has maintained continuity in its quality processes. In addition to energy data, the organization that collects and analyzes basic production data such as production, scrap, and downtime through MES software has been seen to increase its efforts to improve production efficiency based on the obtained information day by day. These obtained data have provided improvements in decision-making processes. It has been observed that energy savings were achieved by eliminating energy losses and theft through the adjustments made to the electrical distribution panels. Within the scope of this study, regression analyses were conducted between the production quantity and the total energy consumed as well as the amounts of different types of energy. According to these analyses, it was measured as 0.006 in 2018, 0.221 in 2019, 0.669 in 2020, 0.711 in 2021, and 0.811 in 2022. The target for ideal energy management systems is for the regression coefficient to be above 0.75 and close to 1. From this result, it can be understood that energy efficiency in the organization has gained positive momentum every year.

The decision to use both historical and real-time data collection approaches was intentional to allow a comprehensive view of the transition from manual to digital monitoring. From 2018 to 2020, data was manually recorded, which may have introduced limitations in accuracy and frequency. However, starting in 2020, the gradual implementation of MES marked a turning point. Full MES integration in 2021 enabled real-time, automated data acquisition, significantly enhancing the reliability and granularity of the analysis. This methodological choice demonstrates the clear benefits of digital transformation on operational efficiency and energy management. As a result, this study has shown that digital factories enable more effective use of production equipment and continuously collect and analyze data. This has allowed for the optimization of energy consumption, enabling more effective use of resources. Industry 4.0 has not only increased energy efficiency but also contributed to environmental sustainability goals. Smart manufacturing processes have accelerated the use of sustainable energy in the industry with their capabilities to reduce waste, save energy, and lower the carbon footprint.

NOMENCLATURE

- **Al**: Aluminium
- **ERP**: Enterprise Resource Planning
- **IoT**: Internet of Things
- **kWh/ton**: Kilowatt-hour per ton
- **MES**: Manufacturing Execution System
- **PLC**: Programmable Logic Controller
- **R^2**: Coefficient of Determination
- **SCADA**: Supervisory Control and Data Acquisition
- **TOE**: Tons of Oil Equivalent

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DECLARATION OF ETHICAL STANDARDS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CONTRIBUTION OF THE AUTHORS

Azat Yakup Şengül: Performed the experiments, analyzed the results, and wrote the manuscript.
Utku Canci Matur: Wrote the manuscript and analyzed the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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