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Editorial

Energy Challenges and Smart Applications in Production Systems

Krzysztof Ejsmont [1,*], Bartlomiej Gladysz [1] and Rodolfo Haber [2]

[1] Faculty of Mechanical and Industrial Engineering, Warsaw University of Technology, 02-524 Warsaw, Poland; bartlomiej.gladysz@pw.edu.pl
[2] Center for Automation and Robotics, Polytechnic University of Madrid (UPM) and Spanish Council for Scientific Research (CSIC), Ctra. Campo Real km 0,200 La Poveda, 28500 Madrid, Spain; rodolfo.haber@car.upm-csic.es
* Correspondence: krzysztof.ejsmont@pw.edu.pl; Tel.: +48-22-234-81-28

1. The Research Background of This Special Issue

A key challenge of the modern world is addressing energy issues, especially in the context of growing public awareness of limited resources and the catastrophic effects of climate change, which are mainly caused by human activity and cumbersome industry. In response to these challenges, European institutions have introduced the Fit for 55 package [1], which aims to significantly reduce CO_2 emissions to achieve climate neutrality by 2050. This package prioritises energy savings in production operations, emphasising the need for industrial change for more sustainable development.

This Special Issue, entitled 'Energy Challenges and Smart Applications in Production Systems', focuses on the challenges of achieving energy efficiency in production systems during the fourth industrial revolution (Industry 4.0) [2,3]. Against the backdrop of growing public awareness of limited natural resources, climate change, and the need to use energy rationally, the authors highlight the crucial role of the industrial sector as a primary energy consumer. The industrial sector accounted for 37% (166 EJ) of global energy use in 2022, compared to 34% in 2002 [4]. Over the past decade, energy consumption growth has been primarily driven by the continued rising production in energy-intensive industry subsectors. Within the industrial sector, the highest energy consumers in the EU in 2022 were the chemical, petrochemical, non-metallic mineral, paper, pulp and printing industries [5]. As a result, Industry 4.0 technologies are being implemented in many sectors, such as paper and printing [6], to reduce energy consumption, among other goals. Increasing energy efficiency requires significant changes in production paradigms and modern, exponential technologies [7].

Despite technological advances, there is still a need to implement new smart solutions. These can include power supply and energy conversion systems, controlling energy consumption in production facilities [8] and greener production technologies [9]. In this context, technologies related to Industry 4.0 and artificial intelligence (AI) offer promising opportunities for energy savings [10,11]. Intelligent solutions can bring many benefits to manufacturing companies, such as reduced emissions [12], lower costs through reduced energy consumption, improved customer service and flexible responses to market needs [13]. Increasingly, manufacturing companies (and SMEs) are incorporating Industry 4.0 and AI technologies into their business models [14]. It is worth mentioning that in many countries (e.g., Poland), SMEs can benefit from energy audits financed by national/EU subsidies to encourage companies to make energy-efficient investments and calculate the rates of return on such investments [15]. An example is photovoltaic installations, which are discussed in the paper [16] in this Special Issue. Tax reductions are also offered to companies that decide to make energy adjustments. The paper [17] presents the impact of tax reduction policies on the green energy industry in China. Sources state that disseminating best

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practices in energy-intensive sectors (manufacturing, transportation) alone can yield up to 20% reductions in energy consumption [18]. Digital platforms are also being developed to offer AI solutions for energy reduction and optimisation in manufacturing [19]. An increasing number of authors recognise the need to apply Industry 4.0 technologies for energy security [20]. This undoubtedly demonstrates the growing interest in digital and smart solutions to reduce energy consumption in production systems and increase the security of energy supplies.

The main objective of this Special Issue was to promote and present new trends and developments related to Industry 4.0 and AI that support energy efficiency in manufacturing and sustainable energy sources. These topics are also covered in other Special Issues of the *Energies* journal, which demonstrates their relevance [21,22].

2. The Contributions of This Special Issue

Five papers underwent a rigorous peer-review process and were accepted for publication in this Special Issue. Their theoretical and empirical investigations focused on various production system issues, and the results obtained allowed the development of solutions to enable energy transformation in the production area.

The authors of [23] focus on designing cooling systems for massive concrete to increase its durability and reduce the heat generated during cement hydration. The study discusses various cooling techniques, such as air cooling using ducted systems and ice water, which is particularly useful for large concrete structures in desert conditions. The use of pre-mix concrete cooling systems is crucial to reduce the impact of hydration heat and increase the structure's durability. Two main cooling system designs are discussed: an air-cooled system that operates via ducting and a chilled water cooling system, highlighting their differences in investment and operational costs. The study showed that, despite the high initial costs, systems based on chilled water cooling are more operationally efficient. Changing to less environmentally damaging refrigerants is necessary due to the increasing regulatory requirements, and also affects the efficiency of cooling systems. Further research on concrete cooling using wet aggregates and its impact on concrete mix quality under different environmental conditions is recommended. This article provides an essential contribution to designing more efficient and environmentally friendly cooling systems for massive concrete to increase the quality and durability of concrete structures.

The authors of [24] present a predictive model for predicting the gradual degradation of conveyor belt voltage in discrete manufacturing systems. The developed model was based on an artificial neural network (ANN) that analysed the energy consumption patterns of the conveyor belt drive under different load and belt voltage conditions. The energy consumption data collected at different load and belt tension levels allowed the ANN model to be trained. The data were collected during the actual operation of the conveyor belt, allowing the effect of belt tension on the transport of pallets between conveyor belt zones to be assessed. During system operation, the predictive model analysed energy consumption and load, predicting the belt tension class. Subsequent inconsistencies between the predicted and optimum tension classes could indicate deteriorating belt tension, leading to failures. The proposed energy consumption monitoring system enables predictive maintenance of conveyor belts, significantly improving discrete manufacturing systems' safety and reliability and avoiding dangerous situations such as belt slippage, material displacement or wear. The authors suggested future research into introducing additional parameters, such as vibration or temperature, to improve the prediction model and increase the accuracy of the predictions.

The authors of [25] present the results of a study on the potential for second-generation bioethanol production in Poland, using lignocellulosic waste as a feedstock. Bioethanol from lignocellulosic waste such as wood, straw and agricultural waste is a sustainable alternative to traditional fossil fuels. This type of bioethanol does not compete with food production, eliminating impacts on food prices. The article also presents a detailed analysis of the costs of second-generation bioethanol production in Poland, considering economic, technical and environmental factors. Among the most essential elements influencing production costs were the costs of purchasing raw materials, energy and labour. The study used game theory to analyse bioethanol production strategies under different economic and social conditions. It was identified that production from wood waste was the most cost-effective method in most scenarios analysed. The proposed technology, considering the recovery and recirculation processes of the process medium, allows for a reduction in energy consumption and labour costs, contributing to higher production efficiency. Wood and wood waste showed the most significant potential as feedstocks for second-generation bioethanol production in Poland, mainly due to their availability and low purchase costs. EU and national subsidies and tax regulations on biofuels significantly influence the profitability of bioethanol production. Tax policies supporting renewable energy sources can significantly influence the development of this sector. An increase in the importance of biofuels in Poland may contribute to reducing CO_2 emissions and meeting the environmental targets of the European Union (EU), provided that second-generation bioethanol production technology is further developed. The authors concluded that second-generation bioethanol, especially from lignocellulosic waste, has excellent potential in Poland but requires appropriate investment, technology and political support to become a viable and environmentally friendly energy source.

The authors of [16] assess the potential for electricity production from small photovoltaic (PV) installations in Poland. Their analysis showed that the most important factors influencing the development of small PV installations in Poland are the costs of energy purchase and the EU regulations on renewable energy sources (RESs). The costs of energy generation from PV installations, the availability of energy resources and changes in social awareness related to the need to use RESs also have a significant impact. A hierarchy of economic, technical and social factors influencing PV energy production was assessed using mathematical and expert methods. Five main factors were central to the analysis: EU regulations, the technical and social feasibility of PV development, the availability of conventional energy sources, environmental aspects and PV power generation costs. The cost of energy production from small PV installations (up to 10 kW) was analysed using the levelised cost of electricity (LCOE) indicator, which in Poland was 0.49 PLN/kWh, lower than the average grid price. In Poland, various subsidies for PV installations have recently become available, significantly improving investments' profitability. Subsidies and tax breaks can significantly reduce the unit cost of the energy produced. Rising energy costs in Poland and increasing environmental protection requirements encourage the installation of small PV systems. EU subsidies and energy production costs have the most significant impact on the development of the PV market. The possibility of benefiting from subsidies and tax exemptions may significantly increase the number of small PV systems in Poland in the future. Small PV systems are more economical than purchasing energy from the grid, which may encourage Polish households to use more renewable energy sources.

The authors of [26] focus on assessing energy flexibility in the cooling process of food production. This study was conducted in a Danish cooling plant producing canned meat. Multi-method simulation and multi-criteria optimisation were used to assess the potential for energy flexibility. The simulation included multi-agent-based simulation, discrete event simulation and system dynamics. A simulation library was developed to represent a typical canned cooling production flow. The OptQuest optimisation tool was used to find the optimal operating schedule for the cooling system. The aim was to minimise energy costs and CO_2 emissions. The simulation results showed that significant energy savings could be achieved by varying the cooling system's operating schedule based on energy price and CO_2 emission forecasts; 32% of energy costs could be saved and CO_2 emissions could be reduced by 822 kg over a weekly production period. Changes in the operating schedule of the cooling system did not affect production quality or throughput, suggesting that energy flexibility is achievable without negatively affecting production. The article contributes to research on energy flexibility in industrial processes, particularly in the meat industry. It emphasises the significant potential for cost and emission reductions, which aligns with the move towards a more sustainable industry. The study provides a comprehensive analysis of the potential for flexible energy management in industrial refrigeration, highlighting the economic and environmental benefits of optimising the refrigeration process in food production.

3. Conclusions

Energy efficiency is, without a doubt, one of the most critical challenges facing modern civilization, and addressing this issue requires profound, transformative changes in how we consume energy, particularly within industrial production processes. Overcoming this challenge demands the development and implementation of innovative systems at both the power generation and energy conversion stages [27,28]. We must adopt fresh approaches and develop advanced solutions to transform how energy is utilised across manufacturing facilities, prioritising integrating energy-efficient and environmentally friendly technologies across all sectors—especially the industries with high energy demands.

In this context, the emergence of Industry 4.0 technologies is crucial, offering new tools and methods to optimise energy usage [29]. These technologies, including intelligent automation [30], advanced analytics [31], and the Internet of Things (IoT) [32], provide an opportunity to significantly reduce energy consumption, streamline operations, and make production more sustainable [33]. This shift towards greener, more efficient systems is not just a goal but a necessity for companies striving to minimise their environmental impact while remaining competitive in a rapidly evolving market.

The papers in this Special Issue highlight that introducing Industry 4.0 and AI technologies to production systems can bring tangible economic and environmental benefits. In order to increase energy efficiency, it is essential to implement new technologies and optimise production processes with environmental considerations. The conclusions point to the need for further research into new technologies and regulatory and financial support for more sustainable industrial development.

The contributions of each paper in this Special Issue can be summarised as follows: Ref. [23] presents a design for a cooling system that allows for more efficient cooling of massive concrete using ice water, reducing energy consumption and emissions; Ref. [24] deals with the predictive maintenance of conveyor belts based on artificial intelligence, reducing energy losses; Ref. [25] recommends that bioethanol is produced from lignocellulosic waste, reducing energy consumption and CO_2 emissions; Ref. [16] confirms that small-scale PV installations can be made more cost-effective through subsidies, encouraging an increased share of RE; and Ref. [26] shows how, through simulation, the scheduling of a cooling system can be optimised, resulting in significant energy savings and reduced CO_2 emissions. Each of these papers contributes to reducing energy consumption by optimising production technology, monitoring processes and introducing more efficient, sustainable solutions. It is worth noting that the results in the presented papers relate to both micro (company) and macro (country) scales, are geographically dispersed (Poland, Denmark, Finland, Jordan) and relate to different methods of production (process, discrete). Various research approaches (experimental studies, models, simulations, expert mathematical methods, cost analysis) were also used. This allows the proposed solutions to be viewed from different perspectives and confirms how important the issue of energy saving is in the manufacturing sector.

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