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# Manufacturing Energy Efficiency and Industry 4.0

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**Abstract:** This Special Issue of Energies was devoted to the topic of "Manufacturing Energy Efficiency and Industry 4.0". To a great extent, this issue follows the successful previous Special Issue on "Energy Efficiency of Manufacturing Processes and Systems", which attracted some significant attention from scholars, practitioners, and policy-makers from all over the world. In total, six papers were published. The main topics included energy efficiency improvement in both the manufacturing process and system levels, as well as how this can be facilitated through the use of Industry 4.0.

**Keywords:** green manufacturing; industrial internet of things; industry 4.0 industrial cyber-physical systems (ICPS); big data management in manufacturing; industrial sustainability; artificial intelligence; machine learning for energy-efficient manufacturing

## 1. Introduction

Energy efficiency in manufacturing systems and processes is a key research topic. Research in the energy efficiency of manufacturing in the last decade has resulted in very promising improvements. While design-time energy efficiency considerations have received considerable attention, operating time efficiency is now increasingly benefitting from the adoption and implementation of Industry-4.0-enabling technologies. The Industrial Internet of Things (IIoT), the upgrade of manufacturing facilities into industrial cyber-physical systems (ICPS), and the efficient exploitation of manufacturing and process monitoring data through advanced Machine Learning present concrete opportunities toward more responsive, smarter, and more energy-efficient manufacturing.

The *Energies* journal has contributed significantly to the field over the years, by giving a place for such research to be published and disseminated. The present Special Issue follows a previous Special Issue on "Energy Efficiency of Manufacturing Processes and Systems" which was concluded in 2020 [1], focusing, however, more on research in the areas of industry-4.0 and how these can have an impact on energy efficiency.

This Special Issue considered the energy efficiency of both manufacturing processes and systems and how these can be improved using Industry-4.0-enabling technologies. The papers invited were focused on areas such as Industry-4.0-enabled methods for the real-time measurement of energy efficiency, machine learning from production line monitoring data for energy efficiency; tools and techniques in the context of Industry 4.0 for the analysis and development of improvements with regard to energy consumption; tools and techniques for the modeling and simulation of energy efficiency; case studies on the management of Industry 4.0 systems for energy efficiency; industry 4.0 and decarbonization of manufacturing; enabling technologies for green, lean, and smart manufacturing; and joint asset and production management aided by Industry 4.0 technologies.

The response to the call for papers led to six published papers. The geographical distribution of the (first) author covers six countries, and is built as follows: Germany, Malaysia, Portugal, Poland, Spain, and the United Kingdom.

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## 2. Background and the Special Issue

As highlighted in the previous Special Issue [1], energy and resource efficiency are approached in a number of different ways, with several methods and techniques and at a number of different levels.

The Special Issue covers a wide breadth of industry 4.0, spanning from high-level frameworks looking at how businesses embrace Industry 4.0 to cases on the use of Industry 4.0 for reducing the energy consumption for specific industrial applications. The papers included in the Special Issue can be categorized into two major groups, the ones that can support strategic decision-making and the ones that are focused more on tactical decision-making.

The "strategic" papers include:

- Szum, K.; Nazarko, J. Exploring the Determinants of Industry 4.0 Development Using an Extended SWOT Analysis: A Regional Study. *Energies* **2020**, *13*, 5972.
- Jiménez-Marín, G.; Elías Zambrano, R.; Galiano-Coronil, A.; Ravina-Ripoll, R. Business and Energy Efficiency in the Age of Industry 4.0: The Hulten, Broweus and Van Dijk Sensory Marketing Model Applied to Spanish Textile Stores during the COVID-19 Crisis. *Energies* **2021**, *14*, 1966.
- Shahatha Al-Mashhadani, A.F.; Qureshi, M.I.; Hishan, S.S.; Md Saad, M.S.; Vaicondam, Y.; Khan, N. Towards the Development of Digital Manufacturing Ecosystems for Sustainable Performance: Learning from the Past Two Decades of Research. *Energies* **2021**, *14*, 2945.

In the following paragraphs, these three papers will be presented and discussed in more detail.

Szum and Nazarko [2] presented a study for assessing the importance of key variables in the development and adoption of industry 4.0 at a regional level. The methodology adapted for the needs of this study are based on extended SWOT. Strengths, weaknesses, opportunities, and threats are identified for the case of a region in Poland, but the method proposed can be easily transferred to other regions as well. The key differentiator to the traditional SWOT analysis is the introduction of four additional dimensions, namely incentives, disincentives, internal opportunities, and internal threats. For filling in the extended SWOT matrix, the researchers relied on an expert group, compiled of 39 experts from the region, resulting in 77 factors. The importance of the factors was then assessed through a seven-level Likert scale and simple descriptive statistics. The authors ranked the factors identifying the ones with the highest importance, thus supporting decision-making and designing implementation plans.

Jiménez-Marín et al. [3] also investigated the factors that impact the implementation of Industry 4.0, focusing sensory marketing on shop efficiency and profitability. Their research addressed the impact of the COVID-19 outbreak as it occurred simultaneously with this research. They empirically analyzed the effectiveness of the sensory marketing techniques using the model of Hulten, Broweus and Van Dijk. An interesting study, with however limited reference to the manufacturing sector, however, the methodology could be easily adapted to a manufacturing setting.

Shahatha Al-Mashhadani et al. [4] summarized the latest developments in digital manufacturing enablers for sustainable product development. They looked into the published literature over the last twenty years through a systematic literature review. The systematic literature review followed the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocol (PRISMA). Implementation of the PRISMA filtering resulted in 52 research articles that were classified into four major research streams, namely digital transformation, digital manufacturing ecosystem, performance management, and sustainability. Among the findings of this study, the researchers highlighted the need for investment in infrastructure, resulting in two different speeds of development, the "fast" one in the developed countries, and the "slow" one for the rest.

The "tactical" papers include:

- Reiff, C.; Buser, M.; Betten, T.; Onuseit, V.; Hoßfeld, M.; Wehner, D.; Riedel, O. A Process-Planning Framework for Sustainable Manufacturing. *Energies* **2021**, *14*, 5811.
- Rocha, A.D.; Freitas, N.; Alemão, D.; Guedes, M.; Martins, R.; Barata, J. Event-Driven Interoperable Manufacturing Ecosystem for Energy Consumption Monitoring. *Energies* **2021**, *14*, 3620.
- Mann, A.; Saxena, P.; Almanei, M.; Okorie, O.; Salonitis, K. Environmental Impact Assessment of Different Strategies for the Remanufacturing of User Electronics. *Energies* **2022**, *15*, 2376.

In the following paragraphs, these three papers will also be presented and discussed in more detail.

Reiff et al. [5] discussed process planning and how this can be organized to facilitate the optimization of environmental sustainability. A novel workflow is proposed for computer-aided production planning. They validated their workflow for the case of the laser metal-wire deposition process. Their analysis considered the resources and consumables required for manufacturing a case product. One of the key elements of this work is a life cycle assessment model that works in the background. The proposed framework and workflow allowed the comparison of a number of scenarios, allowing for the optimization of the process planning while considering the environmental impact of the alternative process's plans. The work presented does not explicitly include industry 4.0 references, however, the approach developed can obviously be further extended to allow for integration with physical manufacturing systems and processes that industry 4.0 capability can facilitate.

Rocha et al. [6] focused on the interoperability of manufacturing systems with the aim of monitoring and reducing energy consumption. Their approach focuses on monitoring events and energy consumption profiles for the components and the machines compiling the manufacturing systems. They implemented their approach in the automotive sector, specifically for two robotics cells. This study is a very good example of the challenges faced when integrating software and hardware solutions in industrial systems. The proposed work touched upon the exchange of data between systems and identified potential architectures and solutions.

Mann et al. [7] focused on the opportunities associated with the remanufacturing of consumer electronics. The authors combined and integrated two modeling methods, discrete event simulation, and life cycle assessment in order to compare the environmental impact of two different manufacturing solutions, a centralized and a decentralized one. The work touches upon the possible benefits of using industry 4.0 solutions (without, however, naming them specifically) for dynamically updating the data input in the models and helping with the development of decision-making support tools at the technical level.

## 3. Concluding Remarks and Outlook

The Special Issue "Manufacturing Energy Efficiency and Industry 4.0" presents a collection of research articles covering relevant topics in the field. A number of different techniques and approaches were presented focusing on both the strategic and the technical decision-making levels. The collection of papers presented highlights the priorities within the research community with regard to the improvement of the energy and resource efficiency of manufacturing and production systems, and how industry 4.0 solutions can further facilitate this.

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