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Review

Energy Efficiency and Industry 4.0 in Wood Industry: A Review and Comparison to Other Industries

Mohamed Haddouche * and Adrian Ilinca

Wind Energy Research Laboratory (WERL), University of Quebec at Rimouski (UQAR), Rimouski, QC G5L 3A1, Canada; adrian_ilinca@uqar.ca
* Correspondence: mohamed.haddouche@uqar.ca

Abstract: This paper presents a literature review of recent research on introducing the Industry 4.0 approach to improving energy efficiency, especially in the wood industry. While researchers focus on processes, service, and customer concepts, the effect on energy consumption is less addressed in these studies and applications. This paper focuses on previous works that discuss how to apply Industry 4.0 concepts to energy issues, such as to achieve better efficiency and performance for the industry in general and the wood industry in particular. The complexity of the study requires a multistep development. First, we define each concept separately and the relationships between them. Second, we apply a search algorithm to find related articles with specific terms, and then use the PRISMA method to select the most important ones, eliminating duplicates and excluding articles that do not mention energy efficiency and Industry 4.0 in the manufacturing or wood industry. Third, we explain and categorize the results and consolidate the study with brief examples from other industries. Finally, we conclude the study by mentioning the limitations and perspectives.

Keywords: energy efficiency; Industry 4.0; wood industry; Energy Management 4.0; energy devices; smart factory

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1. Introduction

The industrial sector is the most energy-consuming sector before the transport and residential sectors. It accounts for about 31% of the overall energy consumption [1,2]. For this reason, manufacturers are placing increasing emphasis on energy efficiency through improvements in energy management, energy devices, and insulation. Energy efficiency improvement is the application of engineering principles and best practices to control the energy consumption of a facility. It is a continuous process that requires the full involvement of all stakeholders (managers, engineers, workers, etc.) to identify, formulate proposals, and implement energy efficiency technologies and practices to reduce energy consumption. Many technologies and practices are currently available and in development that could save energy if adopted by industry [3], classified into two main categories: energy management technologies and energy devices. In addition, various tools and methods are used, such as energy monitoring tools, process modeling and integration, optimization and simulation tools, energy analysis and decision support tools, etc. [1,4]. One of the recent innovations is the introduction of Industry 4.0 in manufacturing, in other words, the transition to the new industrial era.

In 2011, the term "Industry 4.0" became publicly known. The idea originated as an approach to strengthening the competitiveness of the German manufacturing industry. Since then, many companies, researchers, and universities have been interested in this concept [5–7].

Among the areas of interest for Industry 4.0 approaches, we retrieve manufacturing, logistics, maintenance, and energy. Unfortunately, energy is the least addressed area in this research so far. On the one hand, most Industry 4.0 research focuses on manufacturing or maintenance and gives less importance to the energy area (we will discuss this topic below). On the other hand, the recency of the Industry 4.0 concept and the lack of studies and support make the research more difficult.

The following sections define the most important terms associated with Industry 4.0 and energy efficiency and their relationship, considering the concepts' recency. The representation of each term separately is necessary to understand each concept and determine the relationship. However, the pure definition could not give us the appropriate results, so we define the terms in a specific context and dissect each of them if necessary. Next, we will review the previous articles with the strengths and weaknesses, giving examples for the wood and other industries. Finally, we give the limitations of this study and offer recommendations for future studies.

Part I: Basic Definitions.

2. Energy Efficiency

According to the Quebec Ministry of Energy and Natural Resources, energy efficiency aims to "*make the best possible use of available energy to obtain a better energy yield. Energy efficiency is improved when producing the same good or service with less energy* [8]".

In general, energy efficiency uses the best technologies or controls to reduce energy consumption (LED lighting, hybrid system, management software). Energy efficiency makes operations competitive and economically sustainable by including energy management [9]. Energy management is the continuous monitoring, maintenance, and improvement of energy performance [10]. Its objective is to organize industrial facilities to integrate energy efficiency into their management practices [11].

In industry, energy efficiency can be improved in thermal processing systems through better operation and maintenance practices, process optimization, and good insulation [12]. Energy efficiency is expressed as a ratio of an output (performance, service, goods, or energy) to an energy input [13]. Numerically, it is the result of the ratio of input energy to output energy expressed as a percentage [14]:

$$\text{Energy Efficiency} = \frac{\text{Energy Output}}{\text{Energy input}} \times 100\% \tag{1}$$

Improving energy efficiency is about increasing this ratio through technological, behavioral, and economic changes [15]. Energy efficiency is a shared field between many scientific disciplines such as engineering, economy, policy, environment, management, etc. We will detail the three most influential fields, i.e., economic, environmental, and policy (Figure 1).

2.1. Economic Impact

Economic activities need energy as a source of power. Since the first industrial revolution, fossil fuels such as coal and oil have been the primary energy source. With the increase in energy prices, the concept of energy efficiency has been developed [16]. The relationship between the economy and energy efficiency is an ongoing topic of debate [17]. Previous studies have shown economic and social benefits to consuming energy efficiently [18]. In industry, it is supposed to increase productivity and improve competitiveness [19–21]. However, it is not easy to understand the relationship between economics and energy efficiency because it depends on other parameters.

For example, Rajbhandari and Zhang [19] used data from 56 high- and middle-income economies between 1978 and 2012 to determine a relationship between economic growth and lower energy intensity. They also identified a long-term relationship between lower energy intensity and higher economic growth for middle-income economies. Finally, policy decisions to increase energy prices (carbon tax and emissions trading schemes) can increase energy efficiency trends [19]. This, in turn, can partially or more than fully offset the negative impact of higher energy costs on the economy, a win-win situation [22].

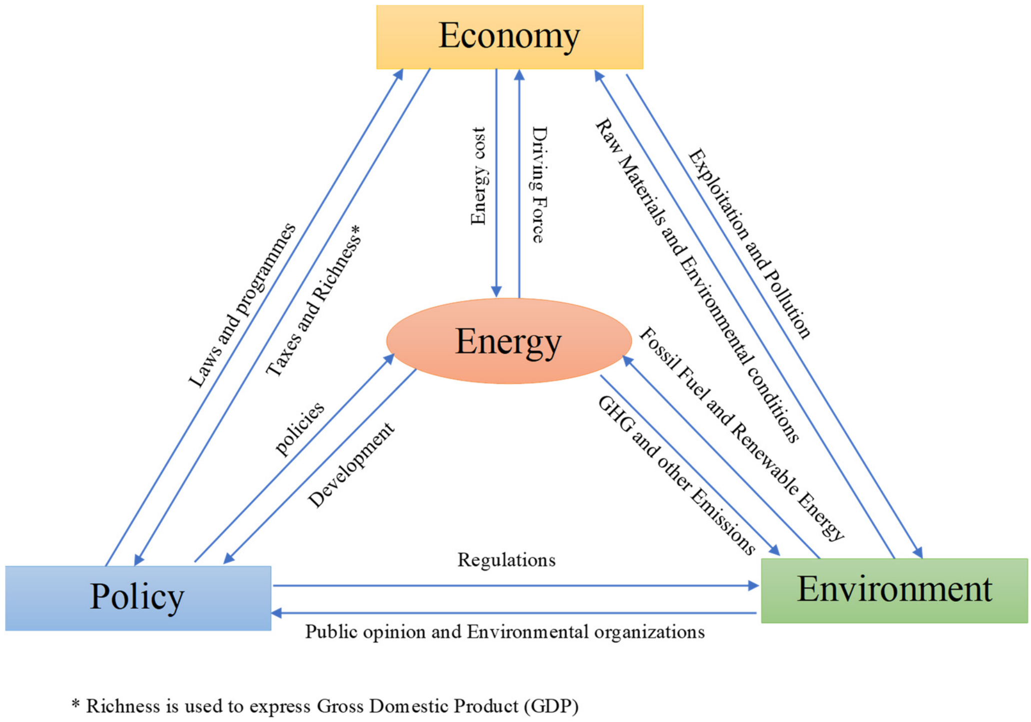


Figure 1. Fields influencing energy development.

2.2. Environmental Impact

In addition to the economic impact, the environment can benefit from energy efficiency, knowing that burning fossil fuels generates energy and the emission of greenhouse gases (GHGs). GHG emissions significantly impact climate change, and the situation is worsening with industrialization, urbanization, and improved living standards requiring higher energy consumption [16], hence the need to improve energy efficiency, manage energy demand, and promote renewable energy production [13]. Furthermore, the adoption of energy efficiency in the industrial sector is one of the key measures to reduce GHG emissions [23].

2.3. Policies and Programs

Most countries have adopted government policies and programs to improve energy efficiency in many areas such as residential buildings, industry, transportation, and utilities. Governments are implementing these essential policies and programs to improve energy efficiency, and industry is making commitments [24].

The International Confederation of Energy Regulators (ICER) established regulatory practices for promoting energy efficiency in its report. Energy regulators have committed to examining the best and promising practices promoting energy efficiency through case studies [25]. The International Energy Agency (IEA) makes 25 energy efficiency policy recommendations across 7 priority areas [26]. In 2019, the Global Commission for Urgent Action on Energy Efficiency was established at the 4th Annual IEA Global Conference on Energy Efficiency in Dublin, Ireland [27].

In 2012, the European Commission issued guidance notes called the Energy Efficiency Directive 2012/27/EU. The EU set an energy efficiency target of 20% by 2020 (relative to projected energy use in 2020) and revised it in 2018 by updating some specific provisions and introducing new elements. It sets an overall EU energy efficiency target for 2030 of at least 32.5%. It requires energy companies to achieve savings of 1.5% of their annual energy sales to the end-user [28,29].

In the United States, the Office of Energy Efficiency and Renewable Energy, in collaboration with other organizations, has developed an energy program called EECBG (Energy

Efficiency and Conservation Block Grant Program). The EECBG program is managed by the Weatherization and Intergovernmental Program (WIP) of the Office of Energy Efficiency and Renewable Energy (EERE) of the U.S. Department of Energy (DOE). The objective of the EECBG Program is to assist eligible entities in developing strategies to reduce fossil fuel emissions, decrease total energy consumption, and improve energy efficiency in appropriate sectors [30,31].

The Canadian Government subsidizes federal programs such as EcoENERGY, while some provinces offer their own programs [15]. For example, in Quebec, the Government has developed an energy policy for 2030 with the following objectives [32];

- Improve the efficiency of energy use by 15%;
- Reduce the quantity of petroleum products consumed by 40%;
- Eliminate the use of thermal coal. Improve the efficiency of energy use by 15%.

3. Industry 4.0

In scientific literature, there are many definitions of Industry 4.0. The term was first announced in 2001 during the Hannover Fair (Industrie 4.0 in German). Moreover, it was officially proclaimed in 2013 as a German strategic initiative that transformed the manufacturing sector [33]. Industry 4.0 refers to the next industrial revolution. This industrial revolution came after three other industrial revolutions in history. The first industrial revolution began in the 18th century in Great Britain and was characterized by the introduction of mechanical production and the internal combustion engine. From 1900, electrification and the division of labor led to the second industrial revolution (examples: the breakdown of production into specialized repetitive tasks called Taylorism or the shift to the assembly line called Fordism). The third industrial revolution, around 1970, was marked by the digital revolution or the automation and robotization of manufacturing, with the advent of advanced electronics and information technologies such as semiconductors and PLCs [5,6] (Figure 2).

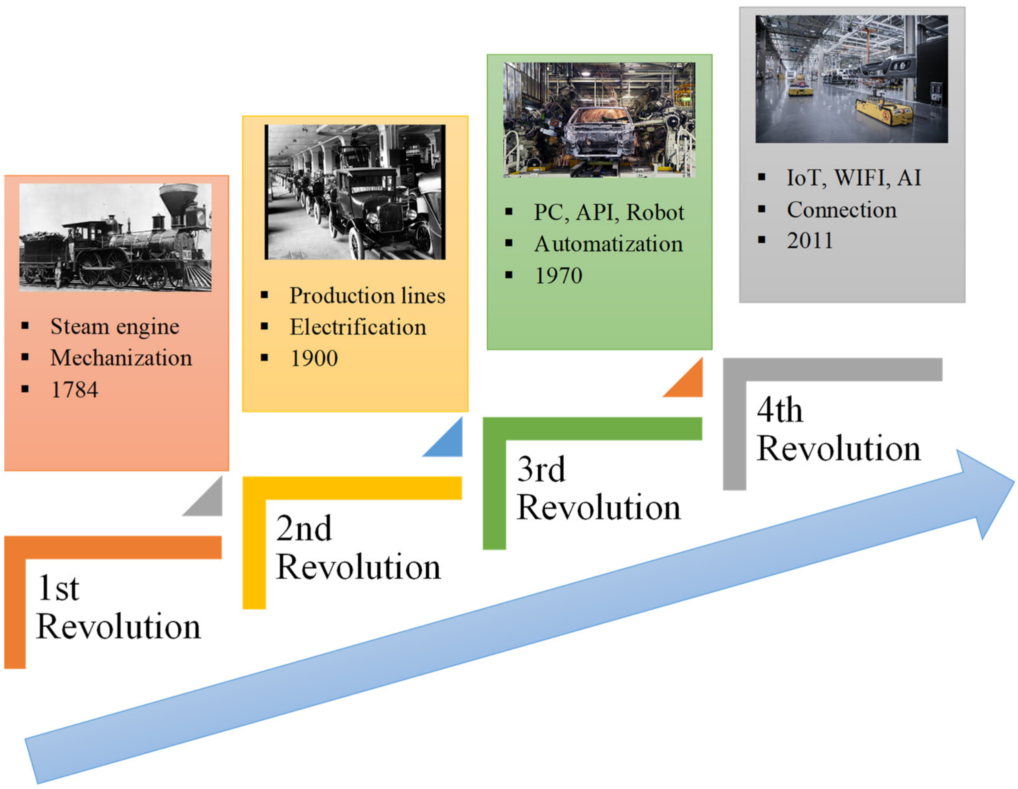


Figure 2. The four industrial revolutions.

The fourth industrial revolution, whose birth we are experiencing today, goes beyond the concept of traditional industry. Instead, it is about the intelligent industry and complete digital integration by giving machines communication, decision, and performance capabilities [6,34].

As a result of the accelerated development of communication technologies, the world is becoming a small village. It is increasingly connected, and customer requirements are becoming more and more precise in a short time [35]. Furthermore, due to the increasing number of intelligent and connected products in the market, industries are changing the management of systems [36]. In this context, Industry 4.0 has the primary mission of creating an intelligent environment from products, procedures, and processes to smart factories. The smart factory is the core of Industry 4.0 (Figure 3) [37]. Therefore, it combines smart sensors, artificial intelligence, and data analytics to optimize manufacturing in real-time [33].

Figure 3. Industry 4.0 and smart factories P.Odoroaga [38].

Industry 4.0 is based on nine pillars [39,40].

3.1. Internet of Things (IoT)

In 2012, General Electric invented the concept of the "Industrial Internet". It integrates the physical and digital worlds that combine big data analysis with the Internet of Things. The concept assumes a much broader application domain than Industry 4.0 and covers power generation and distribution, healthcare, manufacturing, the public sector, transportation, and mining [41–43]. One of the pillars of Industry 4.0 is the extensive use of the Internet, not only as a low-cost channel to connect machines, devices, sensors, and people, but also to create new product functions and features related to the ability to use the Internet as an information source [44]. One of the most straightforward definitions of the Internet of Things is a universal interconnected network of uniform addressed objects communicating with standard protocols [40,45,46].

3.2. Cyber-Physical Systems (CPS)

Cyber-Physical Systems (CPS) are technological systems for managing the interconnection between physical and computational properties of a given system that can interact with humans [47,48]. A CPS is a physical device, object, or equipment that can be transformed into a virtual model in cyberspace. The virtual model monitors and controls the physical aspect, and vice versa; the physical aspect sends data to update the virtual model [49,50]. Therefore, SPCs are central to the vision of Industry 4.0 [51].

3.3. Augmented Reality (AR)

Augmented Reality (AR) is a set of technologies that uses an electronic device to visualize a real-world physical environment combined with virtual elements (e.g., an augmented reality lens) [52]. For example, AR can provide engineers with real-time information to help them make decisions and improve work procedures such as selecting parts, changing layout, dimensions, or properties [39,40]. In the energy domain, AR can also help in decision making to select the suitable energy device (heating, cooling, fan, etc.) based on the requirements or physical and thermal properties.

3.4. Big Data and Analytics

The increasing use of sensors and connected systems creates a high volume of complex, high-speed data called Big Data [48,53]. Collected from various sources, it will be needed to support real-time decision making [39,40]. Therefore, the need for data analysis becomes more critical for factories [53]. Considering this situation, artificial intelligence (AI) becomes the optimal solution [54]. Artificial Intelligence (AI) is a cognitive science characterized by strong development in robotics and machine learning [55]. On the other side, manipulating a big volume of data is risky for security and privacy, and the priority is to ensure their preservation. Therefore, blockchain technology is suitable for Industry 4.0 applications [56].

3.5. Simulation

Simulation is a necessary and economical tool before realizing a new project or in the improvement of an existing product and/or process [57,58]. It allows the physical world to be projected into a virtual model, including the plant, machines, products, and humans [39,40]. Thus, simulation can be a good solution in the energy field to determine the airflow, heat transfer, temperature, etc., especially in narrow areas, where the implementation of sensors is not easy, or for predicting physical phenomena in the case of high risks.

3.6. System Integration (Horizontal and Vertical System Integration)

The main mechanisms of the industrial organization are integration and self-optimization [59]. Integration in the vertical and horizontal dimensions means the automation of communication and cooperation, especially standardized and partially autonomous processes that require minimal human intervention [60,61].

3.7. Cloud Computing

According to the National Institute of Standards and Technology (NIST), cloud computing is "a model for providing convenient, on-demand access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or interaction with the service provider [62,63]". The principle is based on the connections of different devices to the same cloud and sharing information between them. It can be a set of machines and the entire factory floor [40,64].

3.8. Additive Manufacturing (AM)

Additive manufacturing is used to produce prototypes or products in small series. Manufacturers can reduce transportation distances and available inventory by decentralizing additive manufacturing systems [39,40]. Production should be faster and cheaper, and the economic realization of hybrid production systems combines additive manufacturing and fabrication processes [40,65]. The goal of AM is to create prototypes and products with complex geometry [66].

3.9. Autonomous Robots

The new generation of robots is not only used for highly repetitive and low-skilled work but also for medium-skilled routine activities [66]. With the development of M2M (Machine to Machine) and H2M (Human to Machine) concepts, robots are becoming more autonomous, cooperative, and flexible [39,40]. In Industry 4.0, robots can perceive, act, and perhaps even reason in the near future [67]. Autonomous robots significantly improve productivity by ensuring quality, speed, accuracy, and strength [68].

4. Relation between Energy Efficiency and Industry 4.0

Due to the increasing cost of energy, low price competition [69,70], and environmental legislation [68,70], the goal of the manufacturing company is to reduce the total cost of production while maintaining the same quality. On the other hand, the higher objective is the sustainable manufacture of goods with minimum energy [71,72] by developing methods to reduce energy consumption and improve energy efficiency. This can only be achieved by adopting a fully transparent energy consumption in plants, facilities, and machines. Here, energy management is necessary. A data and network management system can control production. Computer systems can be integrated into plants and machines. They can receive values measured by sensors (smart sensors) and controllers, record product data, and operate complex systems. In Industry 4.0, energy management requires an independent platform for remote accessibility of the plant [73].

Therefore, Industry 4.0 is applied to the energy efficiency domain in two ways: energy management and energy devices. In the following section, we will show how Industry 4.0 improves energy efficiency by improving energy management and energy devices and the different intervention cases of Industry 4.0.

4.1. Industry 4.0 Concepts to Improve Energy Efficiency: Application to the Wood Industry

Regarding energy management (EM), ISO 50001:2011 norm defines it as the "sum of fully integrated or interacting elements leading to the introduction of an energy policy and strategic energy objectives, as well as processes and procedures to achieve these strategic objectives [74]". The pillars of EM are measurement, monitoring, evaluation, and control of energy in manufacturing while maintaining the same production requirements such as quality, cost, and delivery [75]. Energy management aims to guide industrial facilities to integrate energy efficiency into their management practices [11]. In Industry 4.0, energy management will be referred to as Energy Management 4.0. The role of energy management 4.0 is to provide energy data-driven decisions, monitor energy systems, optimize energy consumption autonomously [69,76], and improve energy efficiency. Energy data must be collected and synthesized from smart meters, sensors, and other tools (energy devices) [77,78] and then integrated into production management [77].

Energy efficiency addresses three cases: building, machinery, and process.

4.2. Buildings

Buildings are important energy systems, with the latest research showing that they are responsible for 40% of total energy consumption and 36% of greenhouse gas emissions [41]. New buildings' energy efficiency technologies are more accessible to implement than old buildings or renovations [12,41,79]. Thus, controlling and reducing the energy consumption of buildings is a real headache. There are three main actions to improve energy efficiency in buildings. The first is to improve insulation to reduce heating and cooling costs. The second is to adapt the automatic control systems of building management. The third is to modify the energy technologies used by changing the lighting devices (installing LED lamps) and using sensors and actuators to automate energy management. In the past, installing sensors and actuators required a significant modification of the building structure. However, newer technologies introduce so-called "smart" sensors and actuators and can use wireless communications, which has a technology and cost advantage. The integration and development of IoT-based smart sensors, devices, and protocols can help in the transition to smart buildings [41]. In addition, Energy Management 4.0 is designed to control heating, cooling, ventilation, and thermodynamic systems by using data received from sensors and devices and processing them with artificial intelligence technology [18,80]. It allows organizing energy activities between consumers and suppliers by coordinating energy production capacities and consumers' needs [80].

4.3. Machinery

Nowadays, economic energy consumption is one of the main concerns of industrial companies in Industry 4.0 manufacturing systems [77]. The energy consumption of machining must be monitored in real-time to achieve efficient energy consumption (energy-efficient production). Nevertheless, it is not easy to establish an energy consumption model. Therefore, Industry 4.0 can provide a solution by deploying various smart sensors, collecting energy consumption data, and applying an AI method to determine energy demand characteristics. For example, a deep neural network (DNN) is a machine learning method that processes and analyzes Big Data to define manufacturing equipment's energy consumption characteristics or trends based on the data obtained from energy consumption monitoring [76]. It proceeds afterward by modifying and optimizing the equipment parameters without human intervention [41].

4.4. Process

Manufacturing processes involve many physical mechanisms to transform raw material into a finished product by changing its form and/or composition [81,82].

Compared to the total energy consumed, the energy spent in the process itself is small [82]. However, it is not negligible because the energy consumption of various industrial processes varies with time and the dynamic nature of the process energy [79,83].

Energy consumption awareness should be raised first, and then energy consumption should be monitored and analyzed in real-time to improve energy efficiency and optimize manufacturing processes' energy consumption [1]. Most standard production systems cannot collect energy consumption data in manufacturing processes [1,84]. In this regard, Industry 4.0 contains dynamic, efficient, automated, and real-time process communication for managing and controlling a dynamic manufacturing environment using the IoT [77].

In addition, the IoT uses data acquisition and control systems to sense, collect, store, analyze, display, and control facility processes [85,86]. Data are collected by smart sensors or other measurement equipment [85] and processed to provide information. The data collected from smart sensors are stored as Big Data by analysis tools [76] in the cloud [77]. Then, they are monitored and analyzed in real-time, integrated into energy management tools (e.g., energy management software, simulation tools), and defined into strategies and practices to improve energy efficiency [77] and reduce energy consumption [41].

5. Wood Industry Particularities

As a natural material, wood can produce energy (biomass) or consume energy (furniture fabrication) from trees to final products. This particularity gives it the intermediary position between vegetable plants and solid materials. It undergoes changes as a vegetable plant, such as drying, grinding, and burning, or as a solid material, such as machining, pressing, and folding. The processing of wood products requires extensive physical and chemical processes that consume a lot of energy. The main processes used for wood products are cutting, forming, drying, manufacturing, and finishing (Figure 4) [87]. On the one hand, the increasing cost of raw materials and production and the availability of material sources are forcing manufacturers to optimize the use of natural resources by adopting innovative solutions to save energy [88,89]. On the other hand, environmental regulations force wood processing companies to change their attitude towards energy consumption and management [75].

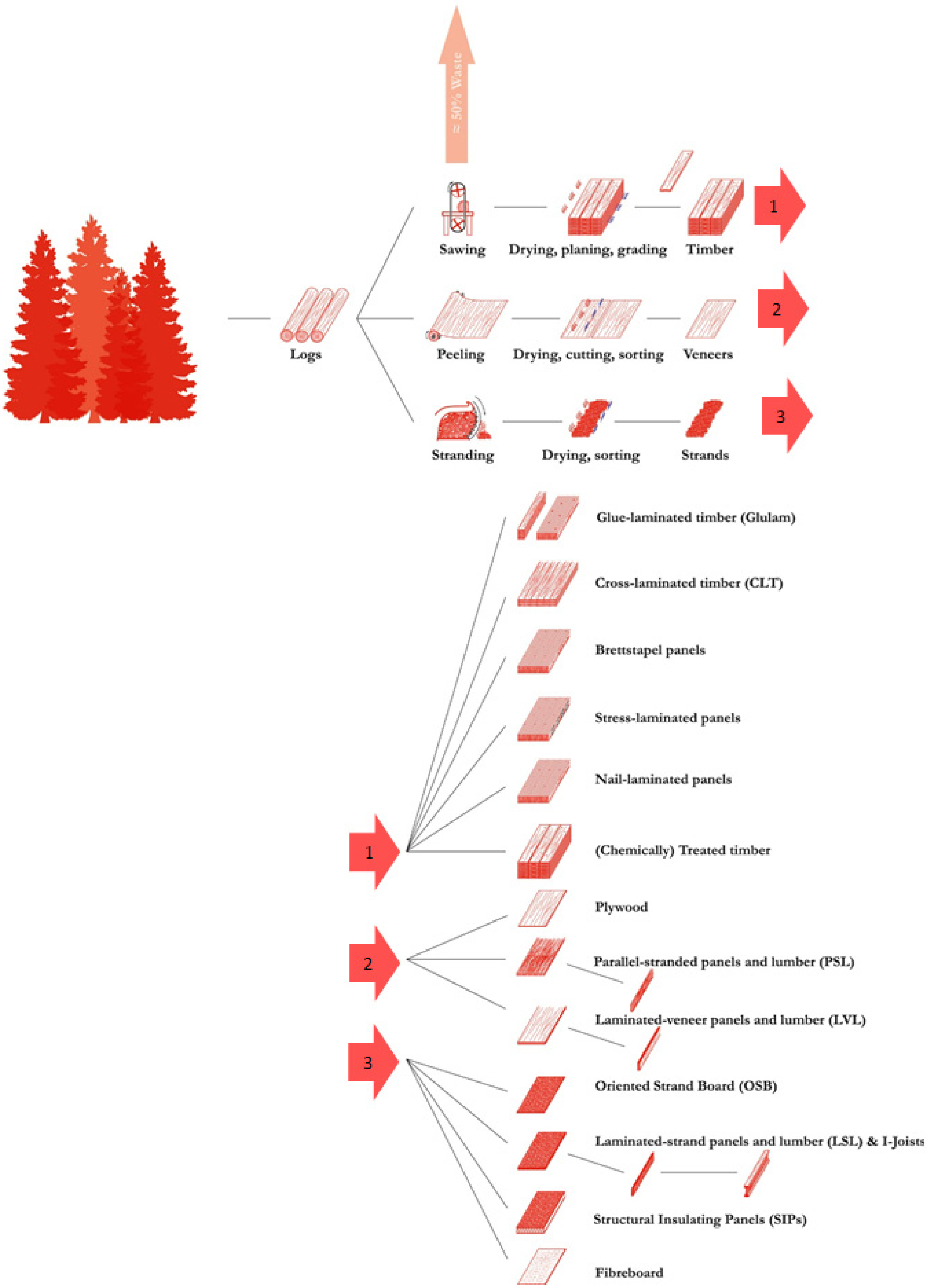


Figure 4. The wood products processing chain P.H. Fleming [90].

Saving energy using the Industry 4.0 concept in the wood industry is a vast and divergent topic. However, we mention two examples to clarify the context. The first example is drying. Drying is a standard process between vegetal and solid materials and is among the operations that consume the most energy in wood manufacturing. Wood drying is an energy-intensive operation, estimated to represent more than 40% of the total energy consumed in the process [91]. To compete, manufacturers need to reduce energy costs by reducing consumption in the drying process and adopting energy efficiency strategies [92,93]. Therefore, manufacturers and researchers emphasize developing energy-saving strategies in the wood industry and adopting recent innovations and technologies. Among them are the IoT and intelligent sensors to collect data from wood and the environment such as wood moisture content, air humidity, and temperature. Then, we treat the Big Data with an AI solution or Energy Management 4.0 system and actuate the dryer (heater and fans) to reduce the energy consumption and ensure the best drying quality. As a result, wood dryer manufacturers propose a new technology called a "Smart wood dryer". The second example is dust collection. Like drying, the dust collection system is one of the most energy-intensive industrial processes, especially for the second and the third transformation. The energy efficiency approach can be applied to dust collection by improving the mechanical and electrical installation and adopting an energy management system [94]. Based on Industry 4.0, Beaulac et al. explain in detail the different ways to improve energy efficiency in the case of cyclone dust collectors. The solution is to adopt an Energy Management 4.0 system that provides energy data such as temperature, velocity, flow, pressure, and dust size [95]; monitors energy systems, and optimizes energy consumption. In addition, equipping the dust collection system with smart energy devices (sensors and actuators) can give the operators the possibility of controlling and reacting in real-time to avoid breakdowns and accidents.

Part II: Review of previous studies on energy efficiency and Industry 4.0, particularly in the wood industry.

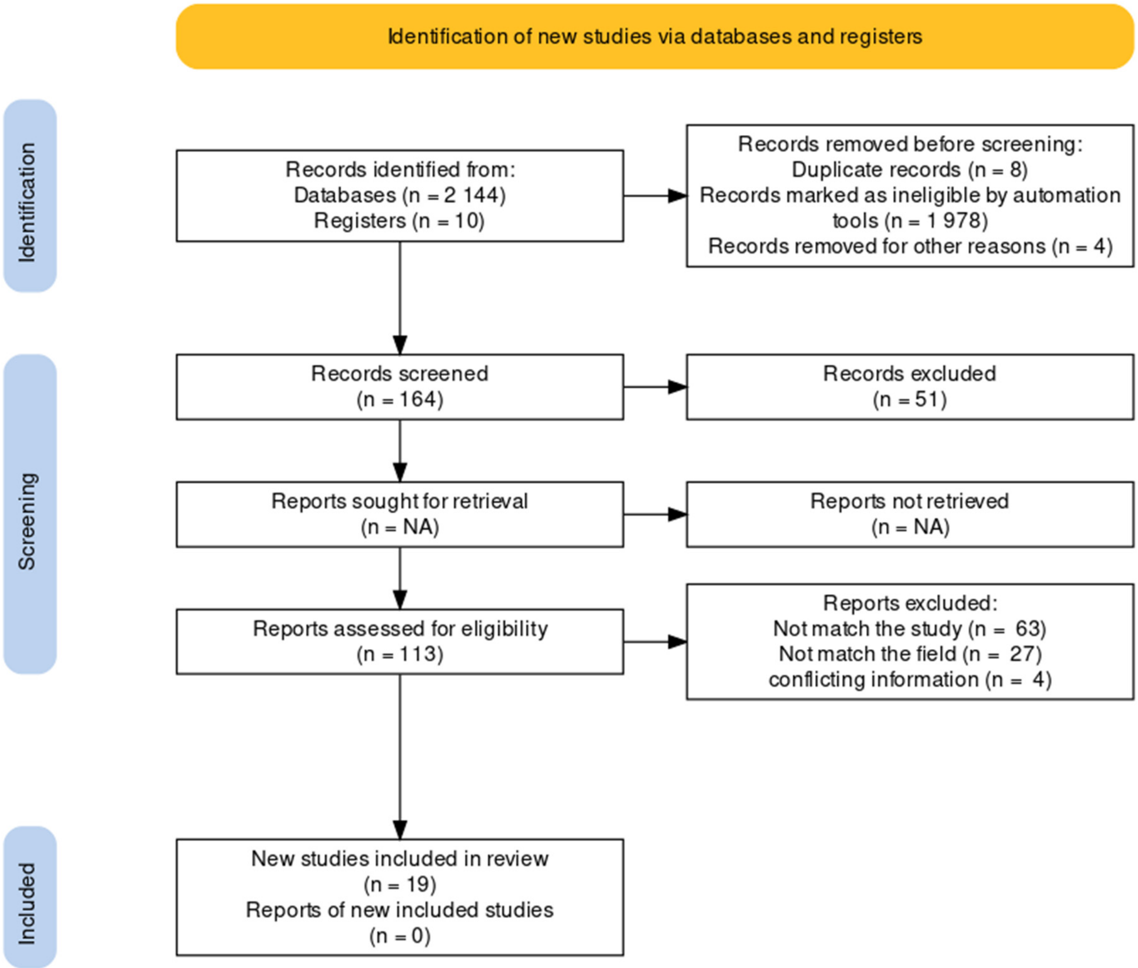
6. Methodology

In this section, we will present the procedures and methods adopted to justify the choices made for the development of this paper. Our study is a literature review of previous research available in the most known databases. Therefore, we will search and classify the articles using keywords (specific terms) and select the articles corresponding to the field using the PRISMA diagram (Scheme 1) [96].

The main research areas are Energy efficiency, Industry 4.0, and the Wood industry. In the literature, most of the previous studies focused on specific terms, for example: addressing energy management and Industry 4.0 (Energy Management 4.0) or energy efficiency with IoT and/or Big Data. Another issue is the peculiarities of the wood industry. For example, most Industry 4.0 studies and applications are related to large-scale industries. On the other hand, the concept of energy efficiency is addressed for energy-consuming processes (e.g., metal casting) or large industries (e.g., automotive industry). As a result, the wood industry is one of the least advanced industries in R&D and innovation compared to the computer and electronics industry, the automotive industry, or the aerospace industry.

Due to the small number of articles in this field and the specialization of those available, we dissect each concept and study the interaction between them. The first thought is "How do we dissect each concept"?

In practice, we can improve energy efficiency in two ways. The first is to choose methods and tools such as energy control tools, process modeling and integration, optimization and simulation tools, energy analysis, and decision support tools: in other words, energy management. The second is to equip the factory with adequate equipment to ensure good air conditioning and insulation and devices such as sensors, actuators, and machines with low energy consumption and reduced connection to each other. In this case, we use intelligent devices connected to an industrial wireless network. Thus, energy efficiency is divided into two terms: energy management and energy device.



Scheme 1. PRISMA flow chart for a review energy efficiency, Industry 4.0 and wood Industry.

As mentioned earlier, Industry 4.0 is based on nine pillars: IoT, Big Data, CPS, simulation, system integration, cloud computing, AR, additive manufacturing, and autonomous robots. However, in the energy space, we do not need all of these. If we refer to previous studies, the most used Industry 4.0 terms in energy efficiency are as follows: Internet of Things, Big Data and Analytics, Augmented Reality, and Simulation. The remaining ones can be treated as "Others". For example, Autonomous Robots are considered a machine. Therefore, the dissection of energy efficiency takes these four pillars, and the rest will be regrouped in "Others".

Our priority is the wood industry for the application, but the number of articles dealing with this industry is small. So, we take the example of other industries and project it to the wood industry, as illustrated in Figure 5.

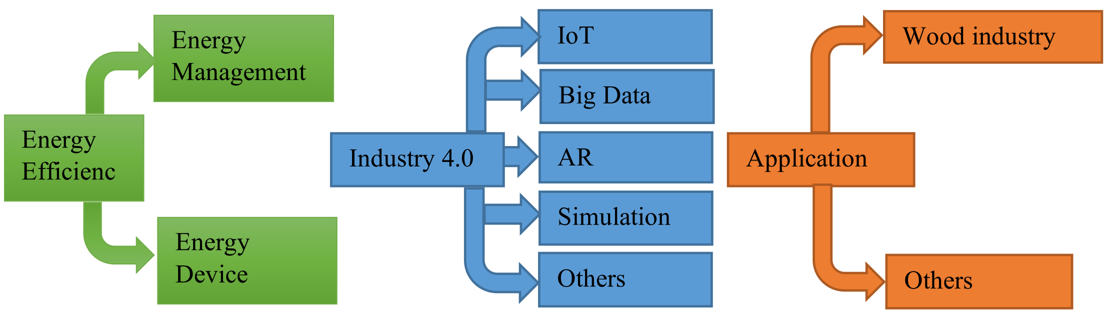


Figure 5. Dissecting diagram of energy efficiency, Industry 4.0, and wood industry.

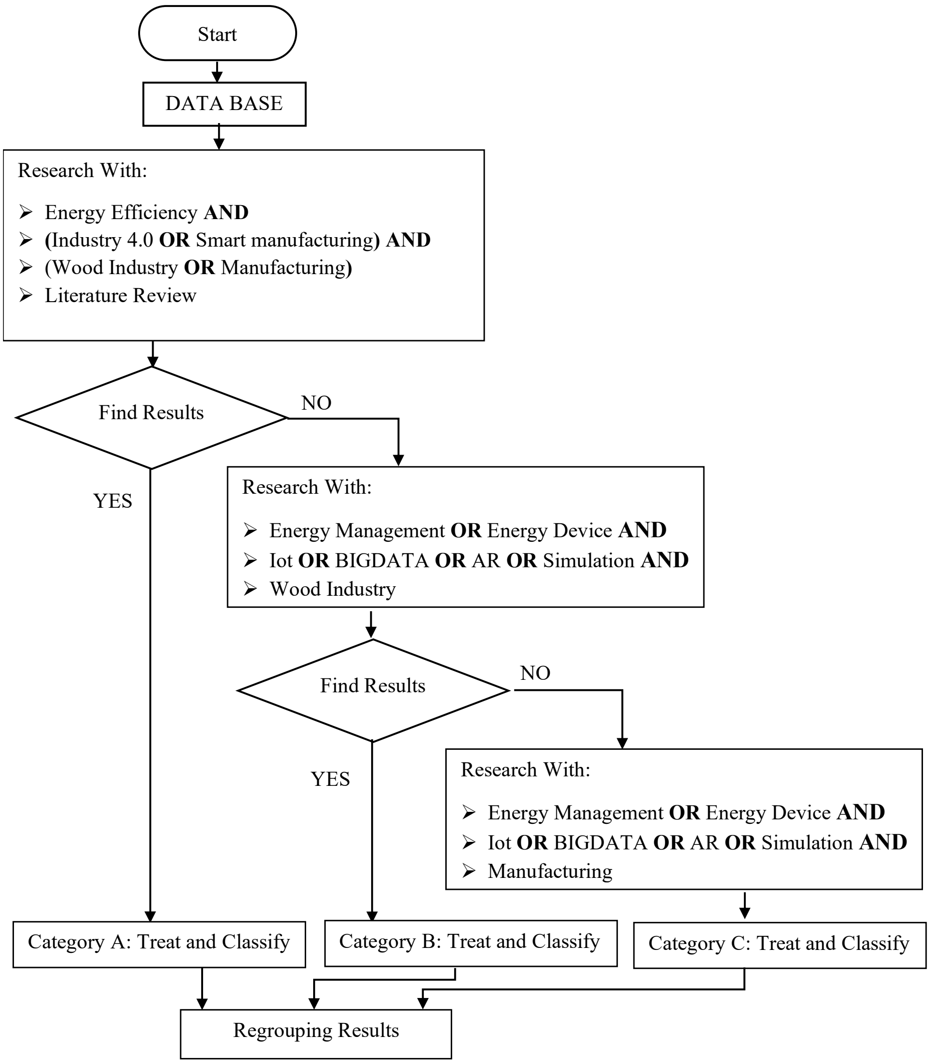
In general, to identify the relationships between energy efficiency and Industry 4.0, we use keywords that characterize all concepts. In this sense, "energy efficiency", "Industry 4.0", and especially "wood industry" have been selected. The databases used are those available on the web (IEEExplore, ELSEVIER, Springer link, MDPI, ACM digital library, ResearchGate, Semantic Scholar).

Due to the diversity of content in technical areas, the robustness of the search, and availability of data analysis tools, the search method used was "energy efficiency" **and** ("industry 4.0" **or** "smart manufacturing") **and** ("wood industry **or** manufacturing"). This section aims to find the previous literature reviews, the methodologies used, and the limitations of each.

The dissection is first conducted by following the keywords and logic as ("Energy Management" **or** "Energy Device") **and** ("Internet of things" **or** "Big Data" **or** "Augmented Reality" **or** "Simulation") **and** "Wood Industry". If there is another term related to Industry 4.0, we will mention it as Cyber-Physical Systems or Artificial Intelligence.

Then, we extend our search to other industries and similarities with our research focus. For that, we follow the keywords and logic ("Energy Management" **or** "Energy Device") **and** ("Internet of things" **or** "Big Data" **or** "Augmented Reality" **or** "Simulation") **and** "Manufacturing".

Based on this methodology, we can illustrate the search algorithm by the following Scheme 2.



Scheme 2. Methodological diagram of the article search.

7. Results and Discussion

The first result obtained gives us 2154 articles. After applying the PRISMA diagram (Scheme 1), the number of results is refined for different reasons (elimination of duplicates, contradictory or insufficient information, exclusion of articles that did not deal with the topic of energy efficiency and Industry 4.0 in manufacturing such as logistics or transportation).

The final number of articles is 19, of which 6 articles deal with the previous literature review, 1 article deals with energy efficiency and Industry 4.0 in the wood industry, and 12 articles deal with energy efficiency and Industry 4.0 with the manufacturing industry in general.

The articles are grouped according to the database source in Table 1 and classified into three categories: (A) Previous literature reviews; (B) Energy efficiency, Industry 4.0, and the wood industry; and (C) Energy efficiency, Industry 4.0, and manufacturing.

Table 1. Classification of articles by the database.

Data Base	Articles
IEEExplore	[73,77,97–99]
ELSEVIER	[71,100–103]
Springer Link	[1,76]
MDPI	[104–106]
ACM digital library	[69]
ResearchGate	[107,108]
Semantic Scholar	[109]

7.1. Previous Literature Reviews (Category A)

In this category, we found six articles presented as follows:

G. Miragliotta and F. Shrouf published a paper in 2013 [1] dealing with the use of IoT to improve eco-efficiency (EE) in manufacturing. They divided the paper into two sections. The first section is a literature review covering efficient energy management and IoT concepts. The second section is devoted to a framework for IoT adoption when engaging in energy efficiency goals in manufacturing.

After a brief definition of the IoT, they categorized the nine articles found according to the domains "Inventory and material management and control", "Shop floor monitoring", "Shop planning and control", and "Production process monitoring and control/machine condition". The small number of articles reviewed is due to its early publication (2013). There were not enough sources addressing the topic.

The framework for IoT adoption was designed by considering the factors of energy type (fixed or variable), EE goals (awareness, improvement, optimization), and existing IT infrastructure that specifies four levels (depending on the current state of the IT level adopted by the plant). In this case, they proposed three scenarios encompassing the fixed and variable energy cost structure:

(1) The first scenario assumes that the IT is at levels 1 and 2. The objective is to increase the awareness of energy consumption.
(2) The second scenario assumes that IT is level 3, which aims to improve energy consumption.
(3) The third scenario assumes that IT is level 4, aiming to optimize energy consumption.

Based on a literature review and expert recommendations, G. Nota et al. [105] tried to reduce the energy consumption required in manufacturing processes by combining management methodologies and Industry 4.0 technologies in the case of batch production processes based on the overall equipment efficiency indicator (OEE). First, a literature review was conducted and classified into three categories: management, technology, and value co-creation. Then, they proposed models based on the combination of OEE analysis and the study of managed variables of CPS manufacturing. Then, they studied the case of

OEE in the automotive manufacturing industry. Finally, based on the proposed models, they determined the causes and quantities of energy waste in a production line.

V. Vianna et al. [108] proposed a classical literature review based on identifying and classifying articles by country, year, and knowledge area and then by points of interest or clusters according to the most cited articles in each cluster. The clusters are the Industrial Internet of Things (IIoT), wireless sensor networks (WSN), energy harvesting (EH), cloud manufacturing (CM), Big Data (BD), program optimization and artificial intelligence (AI), and additive manufacturing (AM). Those who could not be classified into a specific group were counted as miscellaneous. As a result, they presented the interest of each cluster and showed that there is little research compared to the studies on innovation in the same context. They suggested further research in the database used in his work as well as in other databases.

The work of F.S Tesch da Silva et al. [102] is a question-oriented literature review based on the "PICOC (population, intervention, comparison, outcome, and context)" criteria. A set of articles was grouped, selected, and evaluated to answer the queries. In terms of the volume of information, this study is a track to describe energy (consumption and harvesting) and new concerns in Industry 4.0 (radio frequency technologies, IoT, CPS, AI, and Data Science).

The results are presented in a question-and-answer format and tables and address key findings, failures, and opportunities. They revolve around the following themes: Monitoring, Managing, and Predicting, Technologies Applied to Industry 4.0, Industry Challenges, Improving Energy Efficiency.

E.L Vieira et al. [103] used the Proknow-C (Knowledge Development Process-Constructivist) method to determine performance indicators for energy management in manufacturing and Industry 4.0. The method consists of a series of procedures until the arrival of filtering and selecting articles relevant to the research topic. The search is based on three axes: "energy management", "performance", and "Industry 4.0". As a result, they identified 10 relevant articles associated with the research theme. The approaches used in the search and the information about the articles (articles, review, scientific recognition, and keyword cloud) are presented in table and graph form.

In the article by Y. Meng et al. in [106], a review of "enhancing sustainability and energy efficiency in smart factories" was discussed based on the PRISMA framework, focusing on how they interact and benefit each other. Then, critical issues in both areas were identified and discussed. In particular, they discussed the different technologies emerging in Industry 4.0 (Deep Learning, Smart Grid, and Smart Metering, Radio-Frequency Identification (RFID), Big Data Analytics and Data Mining, Cloud Computing and High-Performance Computing, and Additive Manufacturing) and their contributions toward sustainability. In addition, they analyzed the impacts of smart manufacturing technologies on the sustainable energy industry. Finally, they recommend more fundamental research to focus on the challenges and opportunities in combining the two aspects for future investigations.

7.2. Energy Efficiency, Industry 4.0, and the Wood Industry (Category B)

In this category, we found only one article.

Z Pödör et al. in [107] presented a practical study of different industrial IoT solutions in the wood industry's processes and how they are introduced in the target to reduce the energy cost. First, they defined various approaches and techniques associated with the concept of Industry 4.0. Then, they took two different Hungarian factories in the wood industry and applied systems related to industrial IoT.

The first example shows a prototype system for data management (collection, storage, analysis, and process representation) in an industrial wood company. They attempt to perform continuous data analysis using the prototype system. Information is retrieved about past events and estimates of possible future events are provided using forecasting procedures. In addition, they focus on real-time events by setting different alarm thresholds to avoid unexpected production stops or excessive energy consumption in the plants.

The second example presents a simple and inexpensive sensor-based infrastructure and the SensorHUB system, which can collect, send, store, and process sensor data for six different machines. The main reason for choosing SensorHUB is its attractive flexibility and the proximity of regional support. Furthermore, the developed mobile application allows filtering and visualization of the collected data and can serve as the basis for a decision support system.

7.3. Energy Efficiency, Industry 4.0, and Manufacturing (Category C)

In this category, we found the largest number of articles in the literature (12 articles).

S. Nienke et al. [69] presented the concept of Energy Management 4.0 as a roadmap on how to optimize production based on energy data and combining energy data with other information collected from production. They proposed a model based on the "Maturity" level of development. This model is based on energy use cases and industry experts. The different cases determine the levels corresponding to its definition.

The first level is "Visibility", characterized in the first step by energy monitoring and in the second step by load management. The second level is "Transparency", characterized by quality management. The third level is "Prognostic capability", characterized by predictive maintenance. The fourth and final level is "Autonomous Self-Optimization Control", this is the highest stage. In this case, the production is defined as "smart". It can adapt to external and internal factors in real-time and identify the best applicable solution. Now we can talk about Energy Management 4.0, which is based on continuous improvement, development, and innovation.

P. Zheng et al. [76] discussed the concept of Industry 4.0 in manufacturing and examined intelligent manufacturing systems. They divided the article into three sections. The first section is a general definition of intelligent manufacturing systems in Industry 4.0. The second section is a representation of scenarios related to each concept and how to use Industry 4.0: smart design (AR integration, smart wearable devices), smart machining (CPS), smart control (CPS and IoT for energy consumption control), smart control (Cloud), and smart scheduling. Based on these scenarios, they represented the technologies and their possible applications for Industry 4. Finally, the third section identified and discussed the challenges and prospects.

Concerning the energy domain, in the section on smart monitoring, they studied the energy consumption of machines and the need to monitor it in real-time. First, they collected data to determine the characteristics of energy demand by smart sensors. Then, they used a deep neural network (DNN) as a machine learning method to analyze large data sets. After that, they studied the data and results obtained by intelligent programming to establish energy management 4.0. Finally, they proposed an autonomous energy monitoring system with self-optimization of energy use and decision-making based on energy data.

O. T Adenuga et al. [71] developed a special tool to estimate energy costs called "Energy Efficiency Analysis Modelling System (EEAMS)". This tool is dedicated to Industry 4.0 applied to a manufacturing plant. They adopted a bottom-up approach using a web interaction platform to use energy cost information. They proposed a sustainable energy efficiency software based on IoT architecture, a big data analytics model, and centralized data for the cloud through the web interaction platform. In addition, they used the "Energy Efficiency Sustainability Framework (EESF)" to define the economic impacts of energy measurement and verification on energy consumption and the environment. EESF is defined as a series of energy performance indicators for monitoring energy performance. Furthermore, they established the Minimum Efficiency Performance Standard (MEPS) specification, which contains several performance requirements for an energy-consuming device, in preparation for issuing energy management certificates (ISO50001). Finally, they used the load profiles from a South African railcar manufacturing plant as a case study to prepare for these certificates.

T. Javied et al. in [73] detailed the concept of the total cloud-based integrated energy management system from data acquisition to data analysis and visualization. The paper starts with the state-of-the-art of Industry 4.0 and energy management. After that, they explained the cloud architecture step by step based on the demonstrator developed at the Institute for Factory Automation and Production Systems (FAPS). The architecture contains the gateway, the message broker, the data logging module, and the data flow structure. Finally, they presented the energy management dashboard called TIEM.

TIEM (Totally Integrated Energy Management) was developed by FAPS (Erlangen, Germany). It is an energy management system that is automated and fully integrated. It allows visualization and analysis in real-time based on the international standard DIN EN ISO 50001.

In addition, in [100], the authors give additional details about TIEM (Totally Integrated Energy Management), comparing the functions offered by the other energy management system available on the market (in Germany) with TIEM. This article aims to demonstrate the compatibility of energy management with the legislative framework of Industry 4.0 by creating energy transparency in production for the system. This can only be achieved by:

- Implementing modern communication technologies and transmission protocols;
- Implementing control and operating strategies for production and auxiliaries;
- Developing hardware and software components that are networked using modern communication protocols;
- Providing control variants and energy performance indicators via a platform-independent web application;
- Developing a multi-user system that supports role-based planning, implementation, recording, and archiving of required work steps.

The paper presents a comprehensive approach for implementing energy management and all requirements in relation to international standards.

F. Shrouf et al., in [77], published an article dealing with the concept of a smart factory, energy management, and the Internet of Things. The objective is to explain the concept of Industry 4.0 and to present the architecture of IoT-based smart factories, defining the main characteristics of these factories in terms of energy management. In other words, they explored how the IoT improves energy efficiency by providing an approach to support IoT-based energy management in smart factories.

After introducing the research methodology and the concept of Industry 4.0, they made the interaction between smart factories and customers in Industry 4.0. Next, they proposed a reference architecture for a smart-factory-based IoT. Then, they discussed the main potential features of smart factories in Industry 4.0. Finally, they identified how the IoT could support energy management in smart factories and proposed an approach to improve IoT-based energy management.

C. Lin et al. [97] work in energy efficiency and group-based industrial wireless sensor networks (GIWSNs) in the production chain. The paper [96] presents the deployment and sleep scheduling of sensors in a GIWSN. After a brief overview of the literature and comparing related work, they described the GIWSN system pool on the theory of symmetries. Next, they simplified the computation in two ways, from multiple pools to a single pool and another medium-sized pool. They then proposed a genetic algorithm and a hybrid harmony search considering deployment and sleep schedules to reduce energy consumption and maximize energy efficiency. Finally, they simulated the proposed method to verify the achievement of energy efficiency.

So far, we have discussed energy efficiency and Industry 4.0 applications in manufacturing. However, these technologies need proper infrastructure and facilities.

J.S Ko et al. [104] dealt with the energy efficiency of the cooling system fan applied to the data centers of Industry 4.0. They proposed several control methods to improve energy efficiency by reducing the energy used by the cooling systems and improving temperature control performance. As we know, data centers are composed of power systems, computer equipment, and cooling systems. The cooling system, which consumes a considerable amount of energy, is essential to keep the IT system in favorable conditions by ensuring the right temperature and preventing failures and malfunctions. This paper used a thermoelectric element as a cooling system and a PI (proportional-integral) controller. They proposed an FPI (proportional-integral fuzzy) method to control the input value of the PI controller, a VFPI (variable FPI) controller to control the output gain of the fuzzy controller, and a VFPI-VL (variable VFPI limit) controller to adjust the output limit value of the fuzzy control. As a result, they obtained temperature holding capabilities of 50.5%, 44.3%, and 32.6%, respectively.

M. Seewald et al. [109] published a paper on the automotive industry and energy simulation. The paper showed improvement methods based on the simulation of energy and resource efficiency of production processes. The concept of simulation-based energy management improves the quality of planning energy-efficient production systems. The objective is to reduce energy costs by improving the control and management of manufacturing. The analysis of potential energy savings was performed by a simulation software called "Plant Simulation (Siemens PLM)". In the future, a connection with production control will become possible. The self-optimization of production systems will be the focus of Industry 4.0.

They analyzed the energy-saving potential in the production areas following the material flow in the body shop and proposed approaches based on energy-oriented control options (Buffer Sizes, Standby Mode, and Slow Mode) that are considered more energy efficient. These approaches will be introduced into the control system. The simulation yielded the following results:

In all, more than 50 studies with different combinations of buffer sizes and upper and lower limits for energy-saving modes were performed. As a result, by increasing the buffer by only one unit, the energy consumption could be reduced by up to 11% with at least the same number of parts produced. Also, by decreasing the output by 0.5% the energy consumption could be reduced by 8.8%.

R. Goldstein et al. [98] presented a theoretical study of the concept of Industry 4.0 and energy (resource and efficiency). They explained how to introduce energy efficiency in Industry 4.0 in the case of fractal production. They used the German industry as an example because of its position among the industrialized countries. By introducing the concepts, technologies, and architecture revolving around the construction of Industry 4.0 based on energy efficiency goals, they proposed a roadmap to a distributed and adaptive industrial system called a fractal production system based on RAMI 4.0 (Reference Architecture Model Industrie 4.0) architecture. They proposed a way to manage it.

K. Zhou et al. [101] presented a comprehensive study of intelligent energy management based on the Big Data paradigm. First, they discussed the sources and characteristics of energy Big Data. Then, they proposed a process model of smart energy management based on Big Data. Then, they developed a systematic review of Big Data analysis in smart energy management by taking the smart grid as the research field.

They examined it from four perspectives: (1) power generation side management (2) microgrid and renewable energy management (3) asset management and (4) collaborative operation. Then, they analyzed and discussed the industrial development of smart energy management from a Big Data perspective. Finally, they indicated the challenges of smart energy management based on Big Data such as data collection, governance, integration, sharing, processing and analysis, IT infrastructure, security and privacy, and professionals.

The article by N. Mohamed et al. [99] studied and discussed the opportunities and benefits of leveraging Industry 4.0 capabilities to improve energy and cost efficiency in smart factories. The article also discusses the roles of Industry 4.0 technologies in implementing these opportunities and benefits. The article then presents a benefits analysis showing such leverage's advantages. In addition, it discusses an enabling architecture and its components that include the CPS manufacturing services layer, the fog manufacturing services layer, the cloud manufacturing services layer, and a blockchain-based service-oriented middleware to support these opportunities. The authors introduce the various concepts, use of terms, and study's background in Section 1. Section 2 is a brief review covering some related work. Then, Section 3 provides background information on manufacturing processes and Industry 4.0. Section 4 discusses several opportunities that Industry 4.0 can offer to improve energy efficiency in smart factories. Section 5 is a general discussion of the roles of Industry 4.0 in improving energy efficiency in smart factories by providing a summary of utilization and cost improvements. Section 6 presents the architecture and technologies to improve smart factories' energy efficiency. Finally, Section 7 provides some benefits analysis, while Section 8 concludes the paper and discusses some open questions.

7.4. Results Mapping

Table 2 summarizes the previous results found in categories A, B, and C. In addition, it gives the classification of each article according to the field of study and detailed information.

Table 2. Mapping of previously published papers in the energy efficiency and Industry 4.0 in manufacturing (especially wood industry).

Articles		Energy Efficiency		Industry 4.0					Application	
Category	Reference	Energy Management	Energy Devices	IoT	Big Data	AR	Simulation	Others	Wood industry	Others
A	[1]	X		X	X			X		
	[102]	X	X	X	X		X	X		
	[103]	X						X		
	[105]	X		X				X		X
	[106]	X	X		X			X		
	[108]	X	X	X	X			X		X
B	[107]	X	X	X	X			X	X	
C	[69]	X			X			X		
	[71]	X		X	X					X
	[73]	X			X			X		
	[76]	X	X	X	X	X	X	X		
	[77]		X	X	X		X			
	[97]	X			X			X		
	[98]	X	X	X	X			X		
	[99]	X	X	X	X	X	X	X		
	[100]	X	X	X	X					
	[101]	X			X			X		
	[104]	X	X		X			X		X
	[109]		X				X			X

Part III: Relation between energy efficiency and Industry 4.0 in other industries.

Most developed industries have adopted Industry 4.0 as a new step for their development. This new paradigm has benefited production, logistics, maintenance, and energy efficiency. This section will give some relevant examples of industries that have adopted Industry 4.0 in the energy field.

8. Automotive Industry

The car manufacturing process consumes more than 700 kWh/vehicle. The percentage of energy cost is 9–12% of the total manufacturing cost. The energy consumed during the entire life cycle of a car can be summarized in four stages: raw material processing, manufacturing, use, and recovery [110].

The reduction in energy consumption can be achieved by an energy-efficient manufacturing system [81,110] by introducing the concept of Industry 4.0. The automotive industry is one of the first sectors to benefit from Industry 4.0, as automotive plants are characterized by a strong presence of IT solutions and machining robots. The relationship between production and IT solutions would be useful in introducing Industry 4.0 concepts through the digitization of manufacturing processes. This transformation can offer energy-saving solutions [105].

Digitization of manufacturing processes requires transparent management of all sources, machines, and equipment; the integration of all necessary data; and making them available in a uniform way [111,112].

9. Metal Casting Industry

Metal casting is one of the most energy-intensive manufacturing processes [113], especially in the iron and steel division. In 2013, the iron and steel sector recorded 18% of the total energy consumption of all industry worldwide [114,115]. The energy efficiency of the steel industry has a direct impact on energy consumption. Therefore, improving energy efficiency should be a significant concern for steel plants [114]. In metal casting, preheating, heating, and drying are the critical stages of energy consumption. Industrial energy intensity can be reduced through technological advancement [114,116]. Industry 4.0 can provide a solution to this problem by adopting the "smart foundry", which claims to be the solution to the challenges of the manufacturing industry. A "smart foundry" is a highly flexible production system that produces individual parts with the highest precision, best quality, and economical energy consumption [117]. However, the complexity and diversity of manufacturing systems require knowledge in the fields of engineering and management [113]. Therefore, Industry 4.0 enhances data by increasing their volume to become the Big Data received from IoT devices. Then, these data are processed in the cloud with appropriate software using AI and then displayed on a monitor, giving optimal solutions to managers in real-time.

10. Food Industry

In developed countries, the cost of energy represents about 2% of the total production costs. The food industry's case [118,119] includes refrigeration, freezing, thermal sterilization, drying, evaporation, heating, and cooling [118]. Therefore, to optimize energy consumption and improve energy efficiency, the process must include energy and power analysis, integration and modeling, simulation, optimization, control, and decision support tools [4].

The food industry has benefited from the Industry 4.0 concept. Thus, energy usage needs to be controlled, monitored, and optimized as much as possible. However, the first challenge is understanding automated production systems, especially energy management systems [120]. The pillars of Industry 4.0 in energy efficiency can be considered as follows:

- IoT and Cloud computing: equipping machines and plants with smart sensor systems and embedded software with connectivity;
- Big Data: receiving data from smart sensor systems generates huge amounts of data, which provides an environment for Big Data systems. Big Data allow for improved process optimization and energy consumption;
- Vision technologies: enabling visualization of energy flows and a training tool for employees;
- Cybersecurity: The role of cybersecurity is crucial in Industry 4.0 and the appropriate safeguards that must be applied to prevent cyber-attacks [120,121].

11. Limitations of This Review

Despite the intent of this paper to be comprehensive, some limitations accompany a literature review. The literature search process is primarily based on the definition of a set of keywords [122,123], so we may not have identified and incorporated all of the keywords necessary to find the relevant publications below or may have missed some relevant studies. Therefore, we cannot guarantee completeness, although we believe we were able to incorporate most of the significant contributions. In addition, the literature selection process may be affected by researcher bias and subjective views. We have tried to limit predispositions by taking as objective a view as possible in the selection process [123]. Then, the complexity of the phenomena, the recency of the concepts (the notion of Industry 4.0 appeared in 2011), and the neglect of the energy efficiency field impact the quality and number of studies found primarily in the wood industry.

12. Conclusion and Recommendations

We developed our strategy to conduct a systematic literature review on Industry 4.0 and energy efficiency in the wood industry during this study. Due to their complexity, we defined each concept separately, unpacked the complex phenomena, and made connections between the concepts. This technique allowed us (1) to better understand the phenomena, (2) to properly select the articles, and (3) to focus on the most significant concepts.

As mentioned before, the junction of three notions (Industry 4.0, energy efficiency, and the wood industry) is not apparent, so we gave examples to show the points of difference and similarity with other industries.

To develop a good literature review in this field of study, we recommend going into detail, studying a practical case, and comparing it with the concepts.

In conclusion, a good literature review is an essential tool for research. Therefore, we hope that our work will help researchers build their next research on this treated topic and use the derived categories in their next work [123].

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