Heliyon 9 (2023) e20547

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

The potential of industry 4.0 for renewable energy and materials development – The case of multinational energy companies

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ARTICLE INFO

Keywords:
Industry 4.0
Renewable energy
Material
Sustainability

ABSTRACT

The study's primary objective is to identify the implications of Industry 4.0 (I4.0) implementation for renewable energy management and materials development. The study aims to establish a new perspective that promotes adopting emerging clean energy technologies. The study adopts a transdisciplinary approach and critical synthesis of existing literature. Thematic analysis and inferences from three case illustrations are used to gain insights into the value and strategies of I4.0 implementation for achieving a sustainable and low-carbon future. The literature review on I 4.0 provides a deeper understanding of its concepts and potential benefits. The study highlights the improved efficiency, productivity, and sustainability that I4.0 technologies, such as IoT, AI, and advanced manufacturing, can bring to various industries. The study's findings have significant implications for the practical implementation of I4.0. By cohesively identifying and addressing economic, regulatory, and technical obstacles, I4.0 can be effectively implemented for renewable energy and materials development. The study is a valuable reference for students, researchers, scholars, and practitioners. It may guide the design and implementation of I4.0 strategies and supports the transition toward a sustainable and low-carbon future.

1. Introduction

The fourth industrial revolution ("Industry 4.0″ or "I4.0″) is defined as (1) the use of digital technologies to increase efficiency and customize production, (2) connected physical assets and intelligent data processing, (3) the emerging strategic importance of cognitive resources and decision making, (4) the emergence of intelligent machines, artificial intelligence (AI), nanotechnologies, and robotics, and (5) the effective use of online data for optimized decisions based on real-time data through the use of analytics, smart decision making, and machine learning [1]. These technologies can improve various industries' efficiency, productivity, and sustainability [2]. In contrast, the renewable energy sector faces increasing pressure to discontinue the use of fossil fuels and transition to sustainable, more cleaner energy sources. Similarly, the sustainable materials sector hopes to mitigate the environmental impact of material production, use, and disposal [3]. Researchers are exploring how Industry 4.0 technologies and approaches can facilitate the implementation and operation of renewable energy systems, such as smart grids, energy storage units, and renewable energy management systems, in addition to sustainable materials development, which is the impetus for this study.

Smart grids are intelligent electrical power systems that apply advanced sensors, control systems, and communication technologies to facilitate the power grid's efficiency, reliability, and sustainability [4]. I4.0 technologies, such as the Internet of Things (IoT) and advanced data analytics, can enable real-time monitoring and control of the power grid and support grid integration of renewable

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https://doi.org/10.1016/j.heliyon.2023.e20547
Received 3 May 2023; Received in revised form 21 August 2023; Accepted 28 September 2023
Available online 29 September 2023

energy sources [5]. Energy storage systems are essential for the widespread adoption of renewable energy, as they allow excess renewable energy to be stored for use when demand is high or when renewable energy sources are unavailable [6,7]. I4.0 technologies, such as advanced manufacturing techniques and materials, can potentially support the promulgation of efficient and cost-effective energy storage systems [8]. Techniques such as 3D printing and digital twinning have the potential to enable seamless and sustainable material production. 3D printing, for example, allows for the production of customized, complex parts using minimal material waste, and digital twinning provides for the simulation and optimization of material production processes and recycling [8].

Materials recycling systems, real-time tracking and optimization of material flow within the supply chain, and sustainable supply chain management practices can all be facilitated through the utilization of I4.0 technologies, such as advanced sensors, data analytics, and control systems [9]. This article explores the potential of I4.0 technologies and approaches for renewable energy and sustainable materials development. We focus on successfully implementing these technologies in these sectors and discuss the key challenges and opportunities for further adoption. To better understand the potential of Industry 4.0 applications for establishing sustainable production and effective energy systems with renewable energy materials, the following questions must be answered: "What are the latest developments in I4.0 for renewable energy and sustainable materials development (QR1)?". Additionally, "What are the key challenges and opportunities for implementing I4.0 in the renewable energy and sustainable materials sectors (QR2)?"

The motivation for this research is the study's exploratory nature and the limited knowledge surrounding the implementation of I4.0 in the context of renewable energy and materials development. This area is still in its early stages, and there is a need to understand its current state and progress. The significance of this research lies in its comprehensive coverage of topics related to I4.0 technologies and the energy sector. It offers viable solutions and materials development strategies that can drive progress in integrating renewable energies and materials into the industrial sector. Additionally, the study identifies critical challenges to implementing I4.0 applications for sustainable and effective energy materials and renewable energy systems. The objectives of this research are threefold: To conceptualize the potential of renewable energies and materials development in the context of Industry 4.0, focusing on promoting their adoption and implementation in the industrial sector. To explore how I4.0 technologies and materials can enhance sustainability in the energy sector, considering their impact on efficiency, productivity, and environmental considerations. Identify and address the seven critical challenges of implementing I4.0 applications for sustainable and effective energy materials and renewable energy systems, including economic, regulatory, and technical barriers. The novelty of this research lies in its comprehensive approach, combining a literature review and thematic analysis of in-depth interviews with experts. This methodology allows for a comprehensive understanding of the current state and progress of I4.0 in renewable energy and materials development. By addressing key theoretical contributions and identifying critical challenges, the study contributes to advancing knowledge in this emerging field.

The following structure organizes the remainder of this article: In Section 2, a conceptual background is provided to clarify the core concepts of the paper. Section 3 outlines the methodology employed in this study. Section 4 presents the results and analysis of the findings. Next, Section 5 discusses the results, including theoretical and practical contributions. Finally, Section 6 concludes the study, outlines limitations and delineates future research directions.

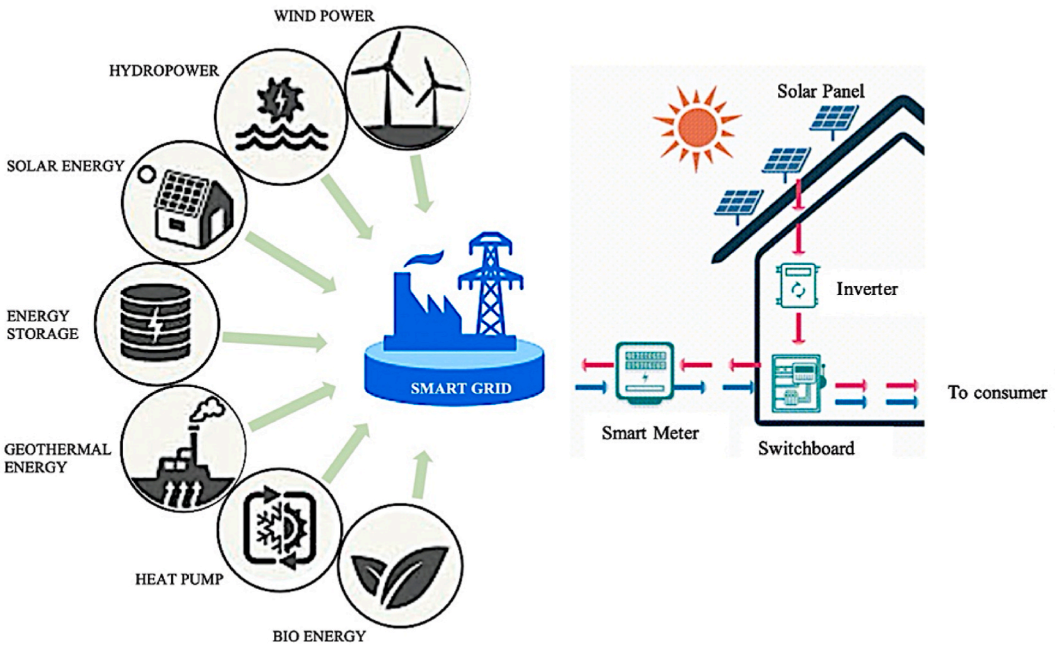

Fig. 1. Viability of renewable energy resources and smart grids to meet customer energy demands.

2. Conceptual background

Industry 4.0 has dramatically affected numerous industries worldwide, bringing about drastic changes and leaving many organizations struggling to keep up with the sudden shift [9]. These changes have completely altered how businesses operate and make decisions [2,10]. Although the research on the impact of I4.0 on energy sustainability is in its nascent stages, several studies are underway to explore the potential of specific fourth industrial revolution technologies to promote energy sustainability. With the emergence of new challenges, professionals and engineers will continue to be pivotal in realizing the objectives of technological progress. Technology development's engineering phase will be crucial in enhancing technology readiness. Sustainable long-term value creation can be achieved through innovative engineering and technical development of products, processes, and systems propelled by imaginative thinking and education [11,12]. According to projections, global energy demand is expected to increase by 25% by 2040, necessitating the integration of Renewable Energy Sources (RES) into the existing power grid infrastructure [4]. However, the adoption of RES can present challenges, including the unpredictability of these sources, voltage and frequency synchronization, immature technology, energy storage, and cyber security concerns [13,14]. Despite these obstacles, continued advancements in renewable energy technologies, energy storage solutions, and smart grid infrastructure are improving the viability and effectiveness of this approach. Fig. 1 outlines the integration of Renewable Energy Resources and Smart Grids to Meet Customer Energy Demands. By leveraging these technologies, we can strive to create a cleaner, more resilient, and customer-centric energy future.

Many industrialized, emerging, and developing nations are constructing large-scale solar and wind farms due to the decreasing cost of renewable energy technology and the realization of the need to reduce energy imports. Countries such as China, the United States, India, Australia, Germany, Chile, Spain, and many North African and Middle Eastern nations have implemented renewable energy initiatives. The digital industrial revolution has presented an opportunity to make energy sources more accessible, financially viable, and environmentally acceptable while increasing energy efficiency and reducing energy waste. The smart grid system, through the incorporation of advanced technologies and digital communication, enables more efficient management and distribution of electricity. This enhanced capability overcomes the limitations of traditional grid systems, which often struggle with handling the intermittent nature of renewable energy sources and ensuring a stable power supply.

The literature [15–17] supports this argument by providing evidence, research findings, and insights related to the advantages of smart grid systems in addressing issues such as grid variability and intermittency, discussing the potential benefits, cost-effectiveness, environmental impact, and other relevant aspects of implementing smart grid technologies. Legal frameworks and innovations in industries have been researched to ensure the successful implementation of smart grids [18]. To ensure secure and dependable supplies of materials for renewable energy products and the production of novel materials, the advancement of I4.0 in the materials development sector is critical [19]. Certain mineral commodities are necessary as raw materials to build infrastructure for renewable energy sources, including solar panels, wind turbines, and batteries. These include silicon, aluminum, copper, and lithium. The impact of I4.0 on the extraction and processing of these mineral commodities is potentially significant [20,21].

The deployment of automation, data analytics, and artificial intelligence has recently bolstered the effectiveness and output of mining and processing operations [22]. I4.0 technologies empower professionals to optimize resource and equipment utility, decrease energy consumption and waste, and heighten safety standards in mining environments. Nonetheless, the extraction and processing of mineral commodities may instigate adverse outcomes, encompassing environmental degradation and social and labor complications [23]. Advanced technologies, such as I4.0 or Fourth Industrial Revolution technologies, may revamp the tracking and administration of environmental impacts and create more energy-efficient materials and processes. The present work investigates the application of I4.0 technologies in the industrial domain and their potential to foster the development of sustainable materials and clean energy. This study seeks to address current research gaps by offering novel insights into the capabilities of I4.0 technologies in these domains.

2.1. Exploring the role of I4.0 in the transition to clean energy and sustainable materials production

The energy sector plays a significant role in global greenhouse gas emissions, comprising two-thirds of such emissions [9,24]. Therefore, accelerating the adoption of clean energy is crucial to address this issue. Solar power systems have shown significant growth, with a 46.2% increase in use from 1990 to 2014, but fossil fuels still account for 78% of global energy consumption [25]. I4.0 can be a powerful tool in the transition to clean energy, providing innovative solutions that reduce environmental impacts. At the same time, domestically-driven initiatives, such as adopting technologies and policies, can improve the energy efficiency and operations of emerging economies' energy sectors. Additionally, regulatory policies that offer long-term, low-interest rate financing can be especially advantageous to small- and medium-sized enterprises (SMEs), as demonstrated by Pradhan and Mbohwa (2014) in Ref. [26].

In the renewable energy production sector, I4.0 technologies are being used to improve renewable energy systems' efficiency, reliability, and scalability [27]. Several scholars have reviewed this concept in the literature. According to literature, IoT sensors and data analytics can be used to monitor and optimize the performance of solar and wind energy systems, while artificial intelligence algorithms can predict and prevent equipment failures [28]. Similarly, I4.0 technologies are also being used to develop new renewable energy sources, such as advanced biofuels and hydrogen fuel cells [13]. In the materials development sector, I4.0 technologies are being used to improve the efficiency and sustainability of materials production processes [29]. Data analytics can optimize raw materials and energy use in producing solar panels and wind turbines, while artificial intelligence algorithms can design and synthesize new materials with improved performance characteristics [28]. I4.0 technologies have also been used to develop new types of materials with enhanced durability and recyclability, which can reduce the environmental impacts of materials production and use [30].

The influence of I4.0 on the renewable energy production and materials development sectors is significant, as these technologies enable the development of more efficient, reliable, and sustainable systems and materials. Research has also focused on developing

Table 1
Materials that can Contribute to the Advancement of Renewable Energy.

	Materials	Uses	Literature
Solar Panels	ARSENIC	Gallium-arsenide semiconductors for solar cells are made using high-purity arsenic.	[32–36]
	GALLIUM	used in copper-indium-gallium-diselenide thin-film solar cells and gallium-arsenide solar cells.	[34,36–40]
	GERMANIUM	Satellites frequently employ solar cells made of germanium.	[41–45]
	INDIUM	used in thin-film solar cells with copper, indium, gallium, and diselenide.	[36,39,40,46]
	TELLURIUM	a component of cadmium-tellurium thin-film solar cells.	[35,36, 47–49]
Wind Turbines	ALUMINUM	Most of a wind turbine's components, especially the nacelle, where wind energy is converted to electricity, are made of aluminum.	[29,50–53]
	RARE-EARTH ELEMENTS (neodymium)	Rare-earth elements make some of the planet's strongest and most effective magnets, allowing wind turbines to use lighter, more compact generators.	[54–57]
Batteries	COBALT	Cobalt is most commonly used in rechargeable battery electrodes on a global scale.	[23,58]
	GRAPHITE	In many lithium batteries, graphite acts as the electrode.	[59–63]
	LITHIUM	Lithium has a long history in batteries and is still frequently used today.	[58,64, 64–67]
	MANGANESE	In many lithium batteries, manganese acts as an electrode.	[68–71]

new materials to advance renewable energy resources (Refer to Table 1). The sustainability of a production process is contingent upon effective energy management. Real-time data acquisition and energy consumption analysis are ways to increase energy efficiency and productivity [19]. Transparency constitutes a crucial factor to ensure that energy usage is appropriate and the effectiveness of implemented measures can be assessed. In this regard, automated solutions, such as field energy measurement systems, have the potential to provide data on energy consumption as well as machine/plant efficiency. Adherence to the ISO 50001 standard and the implementation of enterprise-wide energy analysis solutions can aid organizations in designing, implementing, and evaluating measures to enhance efficiency, allocating cost to production units, and complying with legal and audit requirements [31].

2.2. Leveraging I4.0 for sustainable energy practices

Real-time monitoring of production, assessment of equipment, and improved communication and visibility of processes are among the ways that I4.0 can enhance energy efficiency [72]. These capabilities can support energy-sustainable product design and intelligent quality control and increase supply chain flexibility and energy efficiency. Consequently, as businesses digitalize and adopt I4.0

Table 2
Sustainable energy management in the fourth industrial revolution.

	Practices	Enablers of Industry 4.0 in sustainable production	Literature
1	Digitalization of the Energy Demand Sector (DED)	I4.0 technologies, including the IoTs and data analytics, can improve energy efficiency in several sectors, including buildings, transportation, and aviation. While such technology may increase energy consumption overall, it can also improve the energy efficiency of digital products and services.	[2,5–7,9,24,75–85]
2	Digital Transformation of the Energy Sector (DTE)	This process increases the effectiveness of power generation, transmission, and distribution through simulation, big data analytics, and sensor-based monitoring. Renewable energy sources can also be integrated by new technologies like cloud demand response systems, smart charging, and peer-to-peer electricity trading based on blockchain.	[5,12,15,24,76,84–86]
3	Improved Production Techniques (IPT)	By 2050, additive manufacturing can reduce energy use by up to 20% thanks to its advantages in lighter products, more efficient transportation, less material waste, and more adaptable manufacturing processes. Due to their ability to function effectively in challenging environments and their contribution to the effective manufacture of products that harness renewable energy, industrial robots and automation can also enhance the energy sustainability of manufacturing.	[9,11,12,18,24,76,80,82,83,87–89]
4	Effective Production Management (EPM)	I4.0 encourages proactive energy efficiency. These features can boost energy management and efficiency in industrial settings, along with sensor-equipped equipment and cloud-based data management tools. In the smart factory, real-time production management and process monitoring can also identify and stop impending machine breakdowns and process fluctuations, creating opportunities for resource conservation.	[2,10–12,20,28,76,77,79–82,86,89–94]
5	Effective Production Planning and Control (EPC)	Manufacturers can address energy sustainability demands by utilizing data mining, artificial intelligence (AI), digital twin technology, and industrial simulation to visualize and simulate material flows, automation, and potential manufacturing bottlenecks. Additionally, through virtual commissioning, these tools can assist in troubleshooting and optimizing production lines or cells.	[2,5,9,10,20,28,79,87,91–94]
6	Intelligent Decision-Making (IDM)	Industry 4.0's information processing capabilities, improved value network communication, and process visibility can support energy sustainability. For instance, IoT, data mining, and big data can gather real-time data from all supply chain points and convert it into useful performance indicators for strategic decision-making.	[2,9–12,18,28,76,80,81,84,88,91,92,94]
7	Innovative Business Models (IBM)	Industry 4.0 connectivity is providing a platform for more outstanding communication between plants, machines, and materials to drive real-time information sharing and decision-making across the company's entire value chain, resulting in an improved customer experience while also decreasing production costs, reducing lead times and increasing the efficiency of quality control. These benefits make Industry 4.0 connectivity an invaluable asset for developing more competitive business models in today's industry.	[5,9,12,21,24,76,78,86,90,93,95,96]
8	Smart Energy Management Systems (Smart EMS)	Intelligent energy management systems can be created and integrated into production management systems in the manufacturing industry using sensors, IIoT, CPPS, and machinery. These systems can monitor energy consumption at each process step in real-time. They also use artificial intelligence (AI) to plan energy-efficient production and optimize energy supply, contributing to greater energy efficiency.	[2,6,7,9–11,15,18,28,78,79,81,83–85,87,89,91]
9	Sustainable Development of New Products (SNP)	Energy-sustainable product design considers the entire product life cycle, from conception to disposal, in the context of Industry 4.0. Digital technologies like virtual reality, robotics, and digital twins are being used to create more energy-efficient products. Project management software and collaborative digital technologies improve the efficiency of efforts to develop new products and promote energy sustainability.	[5,7,11,12,18,20,21,76,77,82,83,88,90]
10	Digitization of Value Chains (DVC)	Industry 4.0 capabilities present opportunities for the development of effective products and services as well as opportunities for the digitization of supply networks and the entire value creation network. Supply chains are becoming more flexible and energy-efficient overall due to digitization and the emergence of new business models like supply chain as a service.	[7,9,11,12,18,21,76,81,82,86,88,91]

technologies, they must manage the technology, processes, people, and expertise as a cohesive unit. To promote sustainable growth in the industrial sector, researchers are exploring ways to optimize energy usage and technology (shown in Table 2). This presents an opportunity for businesses to access sustainable solutions that are economically viable and efficient while producing zero waste and extending the lifespan of products [73]. However, developing new energy systems may be complicated by various factors such as project costs, land availability, geological considerations, and project siting [74]. Innovative strategies for sustainability and models that enable businesses to expand and remain successful over the long term are needed to overcome these challenges.

2.3. Circular economy for energy-related materials and technologies

As we progress towards a net-zero economy, there will be an increased demand for wind, solar, and storage technologies. Researchers are putting in a lot of effort to find ways to make low-carbon technology-related materials, tools, and systems more circular to avoid problems associated with their use. A circular economy is based on maximizing the utilization of resources through a closed-loop strategy, as shown in Fig. 2. This approach reduces the extraction of natural resources, the production of waste, and carbon emissions but also advances environmental justice and strengthens supply chain security.

Circularity has become an increasingly important issue, especially with energy-related materials and technologies. The total installed PV capacity worldwide has recently reached 1 TW, with silicon-based technology being the most widely used. Nevertheless, there are several materials available that offer competitive capabilities. For example, thin film photovoltaic (PV) technologies using silicon and cadmium telluride (CdTe) are well-established and installed on a gigawatt scale in the United States. Given its lower energy and production costs and its versatility in recycling, reuse, and remanufacturing, CdTe is a compelling choice for reducing CO2 emissions and ensuring supply chain stability.

Moreover, compared to silicon-based PV, mainly produced outside of the US, CdTe, manufactured at scale in the US and worldwide, requires less energy for production and is significantly more recyclable at an industrial level. The development of advanced solar technologies, such as metal halide perovskites [97], is significantly impacted by sustainability considerations [98]. These perovskites have the potential to be circular, and their ability to allow low-cost production of high-efficiency tandem devices makes them a crucial technology in reaching the US's CO2 reduction targets. Maximizing energy yield and system longevity is essential to achieve the goal of cost-effective and sustainable photovoltaic deployment. Further, to achieve a fully carbon-free circular economy, wind turbine technology must be constructed with recyclable, repurposable, and reusable materials. This concept is not limited to just photovoltaic systems. A solution must be found to recycle thermoset blades at the end of their lifecycle, as well as to produce recyclable wind turbine blades through the use of reversible thermoplastic resin systems. Recent evaluations have demonstrated that a new biobased recyclable thermoset resin prototype performs as well as or surpasses traditional resins while consuming at least 30% less energy and emitting at least 60% fewer greenhouse gases during production compared to conventional epoxy amines [99].

A successful transition to low-carbon energy sources will depend on using renewable energy sources for machines. However, the cost of labor involved in recycling these components, which contain precious metals and essential materials, discourages recycling

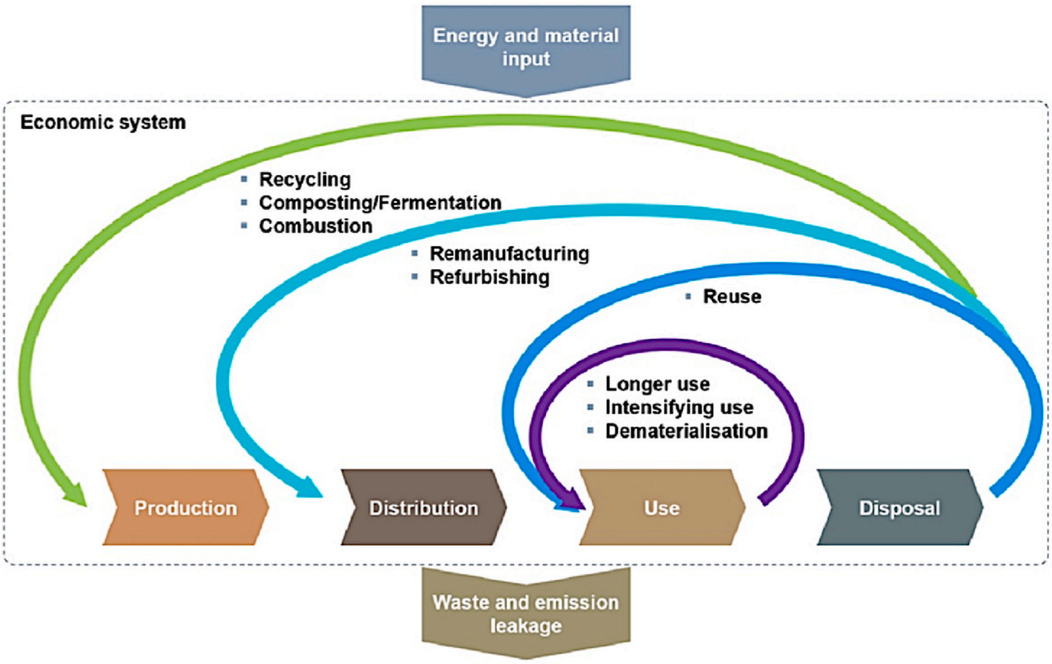

Fig. 2. Closing the circular economy loop [95].

efforts. In this context, rare-earth magnets become even more valuable, as they have precious metals and basic materials and are crucial for producing low-carbon energy sources. Moreover, the cost of labor involved in recycling these components, which contain precious metals and essential materials, discourages recycling efforts. As a result, it is necessary to invest in research and development of efficient processes to recover rare-earth magnets, as this would enable an effective and economically viable transition to low-carbon energy sources. This is especially true given that rare-earth magnets are essential for producing low-carbon energy sources, such as wind turbines and solar panels, increasingly becoming many countries' go-to power sources. The following section delves into the methodology used in the research study.

3. Methodology

The primary step in the present research design entails conducting a literature search employing an integrative review methodology [100]. This approach enables the researchers to collect and analyze a broad range of research findings to uncover novel insights, identify gaps, and supplement the existing knowledge base. Synthesizing diverse perspectives and conclusions from multiple studies provides a comprehensive understanding of the research topic. The research questions for the current research were formulated by identifying the research subject, undertaking a preliminary literature review, setting objectives, and brainstorming potential queries. To prioritize and refine the questions, feasibility, relevance, and impact were duly considered. Insights from field experts were then synthesized to aid in finalizing specific and well-directed research questions that align with established guidelines and objectives [101]. The initial research question, RQ1, aims to guide the empirical analysis of the latest advancements in I4.0 concerning sustainable materials development and renewable energy. Subsequently, in the second phase, we perform a thematic analysis of in-depth interviews with top technical and operations executives aimed at exploring cases that harness I4.0 technologies to promote sustainable materials development and Clean Energy, thereby focusing on RQ2 to gain insights into the possible implications of I4.0 implementation across various sectors. The themes and framework that emerged as we translated the analysis of the qualitative survey and interview data are discussed in the results section of this document. The data collection methodology and the demographics of the respondents are outlined in subsequent sections.

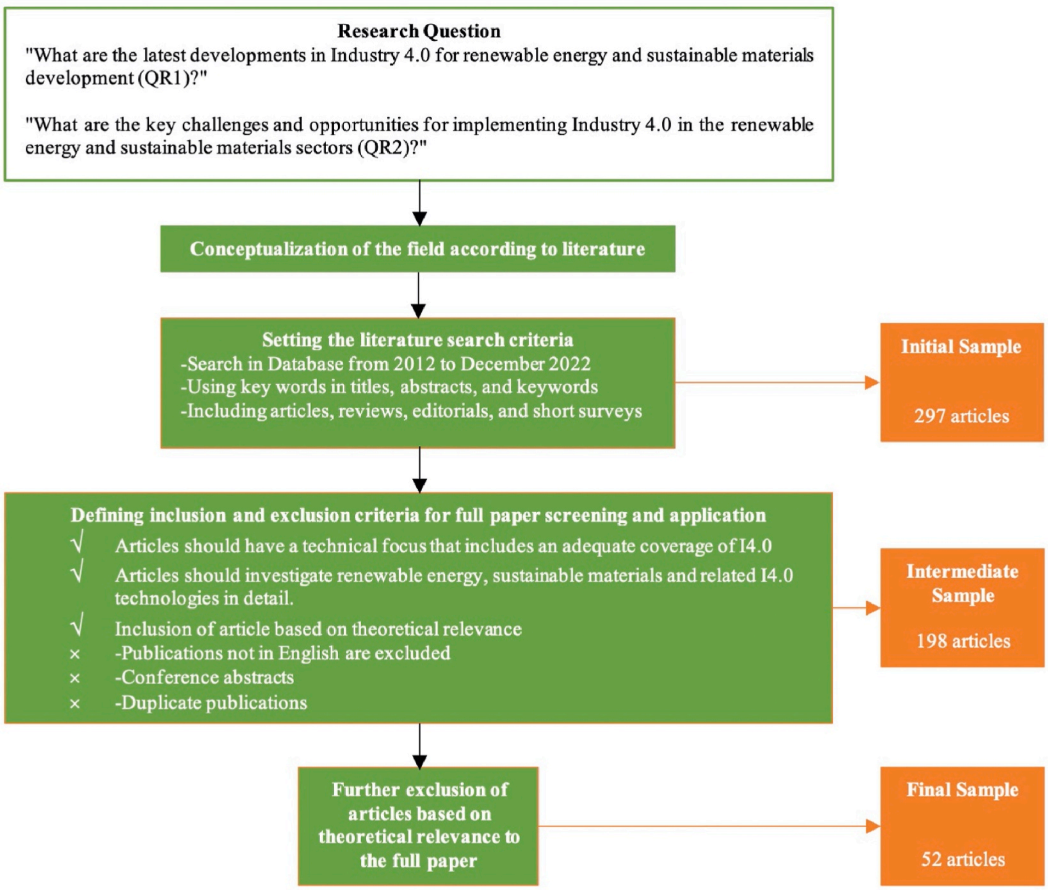

Fig. 3. Flow chat of article screening and selection.

3.1. The literature search process

The literature review provides a systematic overview of the existing research and its alignment with the present study. It covers what I4.0 entails, how it affects various areas, potential solutions, implementation methods, and the benefits of integrating Industry Clean Energy and Sustainable Material Transition. The research focuses on the key challenges and opportunities for implementing I4.0 in the renewable energy and sustainable materials sectors. A theoretical bibliographical sample was conducted from reputable databases such as "Web of Science," "Scopus," "IEEE Xplore," "Springer," and "Taylor and Francis," with the search terms "industry 4.0," "sustainable materials," "renewable energy," and "clean energy" in the title, plus "product," "process," and "system," limited to articles in English published within January 2008 and 2022. Inclusion criteria for studies included peer-reviewed journal publications addressing novel perspectives and the potential implication of Industry 4.0 for renewable energy and nascent materials development, without duplicates. The literature search yielded 297 relevant articles. The steps of the article selection and screening process are outlined in Fig. 3. A research team used a predetermined protocol to ensure comparable data extraction while conducting a qualitative analysis of 52 related articles. The team identified similarities and differences across databases and agreed on I4.0's sustainability functions for clean energy and sustainable material development.

After searching for relevant articles, we analyzed them to identify potential proliferating technological solutions for sustainability. We then created a coding system to map various disruptive technologies and contexts from each research perspective. Finally, we investigated the most recent developments and deployments of Industry 4.0 for renewable energy and sustainable materials and their application strategies through an integrative literature review.

3.2. In-depth interviews with experts and case selection

Various techniques can be used for conducting qualitative interviews, including structured, unstructured, semi-structured, and group interviews. Qualitative interviews are valuable and provide an additional perspective to written practitioner publications, as experts may express their opinions more openly in interviews than in written articles. In this study, we interviewed selected experts who are knowledgeable about our research topic and can provide valuable insights. These experts have had professional experience with different organizations, allowing us to discuss our research topic without direct access to the members of these organizations. In essence, to explore the potential roles of Industry 4.0 in renewable energy and sustainable materials development, we conducted semi-structured expert interviews to gather data and identify common patterns. This research approach allows us to expand upon existing theories and address gaps in the literature related to the practical application of Industry 4.0 for sustainability. Our interviews were intended to collect insights and viewpoints from each interviewee, who was selected based on their proficiency in the industry and their affiliation with a company that served as a suitable case study.

3.2.1. Recruitment and data collection

The study targeted individuals who held management and senior positions in various industries, including the chemical processing industry, manufacturing companies, clean energy, the government, and technology consulting firms. The researchers used social media, particularly the LinkedIn platform, as a recruitment tool to send interview requests to selected participants and also employed a referral sampling approach. This non-probability convenience sampling approach allowed the researchers to access a diverse group of senior professionals, ensuring a broad range of perspectives and experiences. We identified 84 experts with relevant expertise, including experience with digital and Industry 4.0 technologies, innovative materials, energy systems, energy efficiency, and sustainability in the manufacturing and services industry, majorly in sub-Saharan Africa and Europe. For this study, 70 experts across three case studies were invited to participate in an online interview. Unfortunately, some experts declined the invitation, while others had to cancel their participation later due to scheduling conflicts. Eventually, we selected 19 experts for semi-structured interviews based on their experience and job portfolio. During the screening process, four experts were identified as unfamiliar with the fundamental concepts of "Industry 4.0," "energy management," and "sustainable production" and were thus excluded from the study. Ultimately, 15 in-depth interviews were conducted with the remaining experts who were knowledgeable and experienced in the subject matter.

This study employed a purposive sampling approach to investigate the experiences and perspectives of top-level managers in leading companies that have implemented Industry 4.0 Solutions and Renewable Energy and Materials Development. The ethical considerations of this study were taken seriously, with all participants providing informed consent for audio recording, transcription, and the use of their data for research purposes only. All interviewees were also informed of the interview arrangements before participating. Throughout the interview process, we followed the protocol established in previous research [102,103]. We used listening techniques and improvisation (iterative process) to address follow-up questions and cover a range of perspectives on the topic. Despite the smaller sample size of 15 experts, our findings are credible and valid due to the rigorous selection process, the use of semi-structured interviews, and the thorough data analysis methods employed to ensure the validity and reliability of the findings [104,105]. One of the authors carefully considered the specific interviewees' selection and affiliations to ensure a range of I4.0 technological advancements and identify successful and comparable case studies. Four companies were chosen as exemplars of industry leaders in their respective nations, and we used publicly available information was used to corroborate and lend credibility to our findings. Despite potential limitations such as bias and limited generalizability, the results of this study are valuable and informative for understanding the challenges and opportunities organizations face in these cutting-edge areas.

The meetings were held in May and December of 2022 and were conducted online via Zoom. We interviewed each expert (not exceeding 1 h) from the different case studies (shown in Table 3). We used a questionnaire structure that began with warm-up questions (such as name, job title, and employer) and then progressed to more focused open-ended questions [106]. These questions sought to understand the experts' definitions of Industry 4.0, their opinions on the potential of sophisticated technological advances to contribute to sustainability, and their assessments of the willingness of digitized companies to support the transition to renewable and sustainable materials. Our goal was to gather insights from professionals and consultants to identify the potential and desire of these actors to adopt and utilize I4.0 technologies in the clean energy and materials sectors. Specifically, the interview questions centered on three main objectives: 1) exploring participants' opinions and experiences with I4.0 solutions; 2) identifying arguments for and against I4.0 adoption; and 3) outlining trends and subjects of interest related to I4.0 for clean energy and sustainable production. To be selected, the companies had to have implemented IoT, big data and analytics, rapid prototyping, AI, and other Industry 4.0 systems in their sustainable production and energy management. Also, to protect the confidentiality of the experts, their identities have been concealed.

3.2.2. *Data analysis method*

In this "Industry 4.0 Solutions and Renewable Energy and Materials Development" study, we categorized our data by cases and then conducted a thematic analysis using qualitative research rules [107]. Our investigation involved coding the data based on three main aspects: (i) the description of solution autonomy, (ii) the implementation of the solution, and (iii) the stakeholders involved in the implementation process. We compared our coding results to identify any emerging patterns and then categorized the cases based on the categories of I4.0 technology and applicability in our literature review. The authors returned the transcriptions and code of each interviewee to the participants for validation and clarification. To ensure construct validity, We triangulated the collected data with "secondary sources," including the company website and other official company documents available to the public [108]. Our analysis has identified promising solutions and strategies for incorporating I4.0 technologies into renewable energy and sustainable materials development. We believe these findings can inform the development of future sustainable and environmentally friendly solutions. The following section will provide an in-depth look at the study's conclusions, including literature, three companies that have adopted Industry 4.0 technologies, and an analysis of their challenges.

4. Results and analysis

This paper seeks to provide new insights into the potential of Industry 4.0 for sustainable production, energy, and service industries. In the following sections, we will present and analyze the results of our review of scholarly literature on the subject matter, along with semi-structured interviews with experts.

4.1. *Findings from the literature review*

4.1.1. *Articles distribution by research approach*

The team's findings revealed that empirical research was the predominant research approach in the analyzed articles on the current state of sustainability functions in I4.0, particularly in clean energy and sustainable material development. This highlights the need for further case studies and systematic reviews to understand better the implementation and impact of I4.0 on sustainability. All articles' distribution by research approach comprised 49 empirical, 23 reviews, 6 case studies, five systematic reviews, and three conceptual articles. Due to their coverage of multiple research approaches, some articles are counted more than once. The team found that Industry 4.0's sustainability functions have the potential to address environmental challenges and promote sustainable solutions. However, there is a need for more research to identify the barriers and opportunities for implementing these functions in practice. Thus, it highlights the importance of researchers and practitioners collaborating and developing strategies to effectively integrate I4.0 technologies with sustainability goals.

Table 3
Demographics of the interviewees.

Case study	Region	Country	Interviewee ID	Position
CASE A	Europe	Germany	A01	IT Manager
			A02	Consultant SAP
			A03	Senior Project Manager
			A04	Control engineer
CASE B	Sub-Saharan African	South Africa	B01	Senior manager
			B02	Process Engineer
			B03	Senior data scientist
			B04	Materials manager
			B05	Cloud Specialist
			B06	Mechanical engineer
CASE C	Europe	Denmark	C01	Head of a department
			C02	Lead technician
			C03	Principal Consultant
			C04	Operations Manager
			C05	SCADA engineer

4.1.2. Trends in the literature review

Industry 4.0 technologies have the potential to accelerate the transition to clean energy and sustainable materials production [1]. Recently, advanced sensors and data analytics have been applied to monitor and optimize the performance of renewable energy systems, such as solar and wind farms, increasing their efficiency and reducing their environmental impact [18]. Industry 4.0 technologies find use in developing and manufacturing clean energy technologies, such as electric vehicle batteries and advanced solar panel materials, making clean energy more accessible and affordable [58,64]. Automating many tasks involved in producing and distributing clean energy has also been enabled through Industry 4.0 technology, reducing the need for human labor and improving efficiency [9,86]. Other vital technologies, such as 3D printing, the IoT, and AI, have also been utilized to create more customized products using high-end and sustainable materials [5,28]. The common thread among these journal articles is the use of technological advancements, such as Industry 4.0 tools like IoT, cyber-physical systems, 3D printing, big data analytics, and additive manufacturing, etc., to promote sustainability, improve energy efficiency, and utilize renewable energy sources. Table 4 displays the distribution of articles based on the widely used technologies and their associated capabilities. The literature agrees that these technologies are nascent for sustainable energy management and materials development and can help facilitate sustainability in the industry sector.

4.2. A Taxonomy of industry 4.0 for renewable energy and materials development

Industry 4.0 technologies can potentially facilitate the development of clean energy and sustainable materials solutions. Strategies such as automation through robotics and machine learning have been applied to reduce the costs of solar, wind, hydroelectric, geothermal, and biomass installations and operations. Machines and systems can communicate seamlessly through connectivity gadgets like 5G, IoT, Bluetooth, and Wi-Fi. Cyber-attacks have prompted the need to protect systems from malicious actors and unauthorized access. Additionally, improving the accuracy and efficiency of material production processes, including advanced metrology testing, has become paramount. Simulation solutions like digital twins and 3D printing can be used to simulate real-world scenarios for training purposes. To summarize the integrative literature review, we examine the critical industry 4.0 technologies and implementation for developing renewable energy and material solutions, followed by a summary of the integrative literature review.

4.2.1. IoT

The Internet of Things, or IoT allows for devices to connect and send or receive data. IoT can play a significant role in renewable energy management by enabling real-time monitoring and control of material production processes and energy usage in buildings, factories, and other facilities, allowing facility managers to make adjustments from anywhere with an internet connection [1]. IoT sensors have been used to track the energy consumption of individual appliances, lighting systems, and HVAC systems [8]. This can help save energy and reduce costs, thus, ensuring that the materials being produced are as sustainable as possible. In their study, Researchers have explored the use of IoT technology for tracking the use and disposal of materials, thereby facilitating the development of more sustainable supply chain management systems [109]. IoT has also been used to integrate renewable energy systems into existing energy grids, allowing for the efficient distribution of renewable energy to homes and businesses [110]. With IoT, sensors and other devices can be installed on renewable energy generation systems, such as solar panels and wind turbines, or on production equipment and machinery to collect data on their performance, efficiency, and environmental impact. This data can then be used to: optimize energy usage and improve the overall performance of energy systems. Furthermore, IoT-enabled sensors can provide real-time data and data by connecting materials development to the physical world, allowing us better to understand materials' performance in various environments and conditions. In addition, the IoT can enable more efficient product lifecycle management, helping us to reduce waste, conserve resources, and promote a circular economy [111].

Table 4
Key concepts related to industry 4.0 implementation for renewable energy and materials.

Concepts related to industry 4.0 solutions for renewable energy and materials	Characteristics	Literature
Data-driven decision-making or big data	Utilizing data to guide decision-making processes.	[18,81,83,88,105,106]
Robotic process automation	Automating manual, repetitive tasks to make them more efficient.	[73,84,86],
Advanced analytics and machine learning	Leveraging data to identify patterns and improve predictive accuracy.	[26,105]
Smart grid technology	They are utilizing technology to manage energy consumption and distribution effectively.	[4,12,24,32,87,104]
Internet of Things (IoT)	Developing interconnected networks of devices and sensors to gather data.	[1,5,6,21,71,85,103]
Cloud computing	Storing and managing data in a secure, remote environment.	[2,11,76]
Augmented reality	Enhancing real-world experiences with digital overlays or creating entirely virtual environments.	[13,112–114]
Blockchain technology	Establishing secure, decentralized digital ledgers to securely store and share data.	[19,82,109–111]
Additive manufacturing	Utilizing 3D printing to create structures from digital models.	[27,115–119]
Artificial Intelligence (AI)	Developing systems that can learn, think, and act like humans.	[8,10,16,107,108]
Cyber-physical systems	Integrating physical and digital processes to control production.	[25,80,90],
Digital twinning	Creating digital models of physical objects to monitor their performance.	[72,79]

4.2.2. Big data

Big data refers to the large volumes of daily structured and unstructured data generated by businesses and organizations. In management, big data is applied to collect, analyze, and visualize large amounts of information about energy usage, production, and distribution [18]. The information from big data analysis can be used to identify trends, inefficiencies, and opportunities for improvement in the energy sector. One potential application of big data in energy management is the development of predictive models that can forecast energy demand and supply [110]. By analyzing data on past energy usage patterns, weather conditions, and other factors, these models can help energy companies and utilities more accurately predict how much energy will be needed at a given time and plan accordingly. Another potential benefit of big data in energy management is analyzing customer behavior and preferences [87]. By collecting and analyzing data on how and when customers use energy, energy companies and utilities can gain information concerning customer needs and preferences and use this information to develop more targeted and effective energy-saving programs and services.

In the context of green and sustainable material development, big data can help identify potential new materials with desirable properties, such as biodegradable or having a low environmental impact [112]. Big data analytics have been used to analyze large data sets to identify trends, patterns, and relationships that may not be immediately apparent [113]. This can be particularly useful in the field of material development, where there may be many potential materials to consider and where it can be challenging to identify the most promising ones. For example, big data analytics could be used to analyze data on the environmental impact of different materials and their physical and chemical properties. Additionally, big data analytics could be used to analyze data on the cost and availability of other materials, which could help identify sustainable and affordable materials. Using big data in energy management can help companies and organizations improve and develop green, efficient, and sustainable materials and energy systems.

4.2.3. AI

AI entails creating tools and algorithms to analyze data and draw conclusions from it [1,8]. It is a rapidly expanding field, and innovations and uses are continually being found, leading to increased adoption of clean energy sources [114]. AI can also help predict and manage the energy demand, resulting in a more stable and reliable grid [18]. In addition, using AI in renewable energy management can help reduce greenhouse gas emissions by promoting clean, renewable energy sources [115]. Using AI in sustainable material advancement can help improve the efficiency and sustainability of materials production and identify new materials and applications for sustainable development. For example, AI can optimize the production of sustainable materials, such as bio-based plastics and renewable textiles, by improving process control and reducing waste [1,8]. AI can also be used to develop new materials with improved performance and sustainability by combining machine learning algorithms with high-throughput experimentation [114]. However, using AI in this field raises ethical concerns, such as the potential for algorithm bias and the need for transparent decision-making processes. There is also the potential for job displacement in the energy industry and security risks from potential cyber-attacks on AI systems.

4.2.4. Blockchains

Blockchains are distributed, decentralized databases that can store and manage information. It is made up of a series of interconnected blocks, each of which contains a specific piece of information. The blocks are linked using cryptographic techniques, ensuring the data's security and integrity. Blockchains are often used to create and manage digital currencies, such as Bitcoin [116]. In green and sustainable material development, blockchains can track and verify materials' origin, quality, and sustainability [21]. This can help to ensure that materials are sourced and produced responsibly and transparently. One potential application of blockchains in green and sustainable material development is the creation of supply chain traceability systems [117]. Using blockchains, companies can track the provenance of materials from their source to the final product and verify that they were produced sustainably and responsibly. Another potential use of blockchains in green and sustainable material development is the development of certification and verification systems [21]. Using blockchains, organizations can create and manage digital certificates verifying materials' sustainability and quality. These certificates can then be shared with customers, regulators, and other stakeholders, providing a transparent and verifiable way to demonstrate the sustainability of materials.

Blockchains can be used in energy management to track and verify the origin, quality, and sustainability of energy sources and systems [86]. Another potential use of blockchains in energy management is the development of peer-to-peer energy trading systems [118]. Blockchains have been proposed for individuals and organizations with surplus renewable energy to sell directly to other users, eliminating the need for intermediaries [119].

4.2.5. Augmented reality

Augmented reality (AR) technology allows users to interact with digital content in the real world. AR has been used in energy management to visualize and monitor real-time energy usage, production, and distribution [13]. Using AR, users can see how much energy is being used in a particular area or how much power is produced by one specific source, such as a solar panel or wind turbine [120]. A critical potential use of AR in energy management is the development of interactive training and educational tools [121]. In green and sustainable material development, AR has been used to visualize and test materials in their intended environment without physical prototypes. Notably, the application of AR in green and sustainable material development is the creation of virtual models of materials and structures. Another potential use of AR in green and sustainable material development is creating interactive training and educational tools [122]. Using AR, learners can experience and experiment with materials and concepts realistically and engagingly without needing physical materials or expensive equipment [122]. Also, AR users can learn about energy management concepts and techniques more engaging and immersively. Designers and engineers can see how a material will behave in the real world and make real-time adjustments and improvements. This can support the development of more sustainable energy management strategies, reduce the resources and energy required for development and testing, and support the development of new green and sustainable materials.

4.2.6. Rapid prototyping

Rapid prototyping refers to using various techniques and technologies to quickly create a physical or digital model of a product (sustainable materials) or system. Rapid prototyping can be used in renewable energy management to quickly develop and test new technologies or approaches for managing them [123]. It can potentially accelerate the development and deployment of renewable energy systems. It can also identify and address potential challenges or issues before they become significant problems. Rapid prototyping has been applied to develop materials for use in renewable energy systems, such as solar panels or wind turbines, or to create materials for construction, such as insulation or sustainable building materials [87,124]. Some examples of rapid prototyping techniques that can be used in renewable energy management include 3D printing, computer-aided design (CAD) software, and virtual or augmented reality simulations [125,126]. These tools can help quickly create new renewable energy technologies and systems models. They can also be used to conduct virtual testing and analysis to identify potential problems or areas for improvement. Rapid prototyping allows researchers and developers to quickly identify and address potential issues or drawbacks in their designs, allowing them to bring new advanced and sustainable materials to market faster [125–127]. Thus, by quickly creating physical models of new materials, researchers and developers can quickly evaluate their performance and characteristics, such as their strength, durability, and sustainability. Consequently, accelerate the development of materials that are not only environmentally friendly but also have the desired properties for a particular application.

4.3. Findings from expert interviews: case of the sustainability efforts by different businesses leveraging industry 4.0 solution

4.3.1. Industry 4.0 implementation poses several challenges of the development of sustainable and effective energy materials and renewable energy systems

Industry 4.0 technologies have the potential to revolutionize the way materials and renewable systems are developed and used, such as in an environmentally friendly and efficient way. Examples of sustainable and effective energy materials include renewable materials such as solar photovoltaic cells, hydrogen fuel cells, and wind turbines; advanced materials such as carbon nanotubes and Graphene; and energy storage materials such as lithium-ion batteries and supercapacitors. As the potentials of Industry 4.0 have been covered in the earlier section (2.1, 2.2 & 2.3), the experts interviewed for this study identified seven key challenges related to the implementation of Industry 4.0 applications for sustainable and effective energy materials and renewable energy systems, centered around economic, regulatory, and technical barriers. These include (i) High upfront costs, (ii) Limited availability of renewable energy and materials, (iii) Lack of standardization and interoperability, (iv) Cybersecurity risks, (v) Stringent government requirements, (vi) Resistance to change, (vii) Lack of skilled workers.

Based on (i), the high upfront costs of implementing industry 4.0 technologies and renewable energy systems can be a barrier for businesses, particularly smaller ones, that may not have the financial resources to invest in the technological approaches. The experts consider this can limit the adoption of these technologies, which can, in turn, hinder the growth of the industry and the transition to a more sustainable, low-carbon economy. In addition, the high upfront costs can also make it more difficult for businesses to compete with larger, better-funded companies that may be able to invest in these technologies more efficiently. This disadvantage for smaller firms can lead to market consolidation and a less diverse industry. Therefore, businesses must carefully assess the potential costs and benefits of implementing I4.0 technologies and renewable energy systems. Experts are skeptical of the government's support and incentives to help businesses offset the high initial costs associated with these technologies, considering the recent global inflation and financial downturn in both developed and developing economies. Companies must thus consider ways to mitigate potential challenges such as cybersecurity risks, a skills gap, and economic and environmental uncertainty.

Concerning (ii), the limited availability of renewable energy and materials, such as lithium for batteries, can be challenging, as it is not always readily accessible in sufficient quantities to meet the demand for sustainable energy production. Our experts posit that the rising cost of renewable energy production is due to the scarcity of some materials required, such as rare earth metals. Efforts have been made to reduce the cost of these materials to make them more accessible to consumers. These efforts have resulted in increased research and development into alternative materials and technologies that can produce renewable energy without relying on scarce resources. However, there is still a need for improved knowledge, policy, and funding to bridge the remaining technical gaps and overcome these limitations.

Additionally, in (iii), the lack of standardization and interoperability can be a significant obstacle to successfully implementing industry 4.0 technologies and renewable energy systems. Standardization refers to using common standards and protocols for designing, developing, and deploying these technologies. In contrast, interoperability refers to the ability of different systems and devices to work together seamlessly. Without standardization and interoperability, different designs and devices may be unable to communicate or share data, which can hinder the implementation and adoption of these technologies. For example, a lack of standardization and interoperability in the renewable energy industry can make it difficult for different renewable energy sources, such as solar, wind, and hydro, to be integrated into the grid and used together effectively. This can limit the ability of the grid to handle variable, intermittent renewable energy sources and reduce the overall efficiency and reliability of the system. One of our experts, a manager in a manufacturing conglomerate, emphasizes that the lack of standardization and interoperability can make it difficult for different machines and systems to communicate and share data, hindering the ability to automate and optimize production processes. In the context of sustainable materials, a lack of standardization can make it difficult for businesses to evaluate and compare the sustainability of different materials. All our experts agree that without common standards and protocols for measuring and reporting the environmental impacts of materials, it can be difficult for businesses to make informed decisions about which materials to use in their products and processes. This can limit the adoption of sustainable materials and hinder the transition to a more sustainable economy. Industry stakeholders must work together to develop common standards and protocols to overcome these challenges.

On (iv), experts' opinion on the increased cybersecurity risks associated with the widespread use of Industry 4.0 technologies is based on the potential for cyberattacks to affect industrial systems adversely. The implications of these risks could be significant for implementing Industry 4.0 technologies for renewable energy systems and sustainable materials. These risks can include (a) Physical damage to the equipment: In some cases, cyber-attacks can cause physical damage to equipment. For example, a cyber-attack on a renewable energy system could cause a power outage or damage the equipment. (b) Loss of sensitive data: Cyber-attacks can result in the theft of sensitive data, such as trade secrets, intellectual property, and customer information. This can damage an organization's reputation and financial standing and may also result in legal and regulatory issues. (c) Increased costs: Implementing robust cybersecurity measures can be costly, and organizations may need additional staff, training, and technology to protect against cyber threats. (d) Disruption of critical infrastructure: Industry 4.0 technologies often control and monitor critical infrastructure, such as power plants and manufacturing facilities. Cyber-attacks on these systems can cause disruptions to operations and result in significant financial losses. (e) Difficulty in securing new technologies: As Industry 4.0 technologies evolve, it can be challenging for organizations to keep up with the latest security threats and ensure that their systems are adequately protected. This can constantly require organizations to update and improve their cybersecurity measures. In this study, our experts compared the importance of organizations having robust cybersecurity measures to protect against potential risks when implementing Industry 4.0 technologies in the renewable energy and sustainable materials sectors with the need for plans to respond to and mitigate the effects of any cyber-attacks. Such measures may include regular security audits, secure communication protocols, and access controls to prevent unauthorized system access.

Again, all the experts agree on (v), as strict government demands may include regulations around the use of certain materials, the efficiency of renewable energy systems, and the environmental impact of these technologies. This can create barriers to adopting Industry 4.0 technologies in the renewable energy and sustainable materials sectors. For example, if certain materials are heavily regulated or require expensive certifications, organizations may find it more challenging to use them in their products and systems. Similarly, if government regulations set high standards for the efficiency of renewable energy systems, it may be more challenging for organizations to meet these standards. Nonetheless, according to our experts' strict government regulations can be a driver of innovation, reducing reliance on fossil fuels to combat climate change. This can also lead to developing advanced Industry 4.0 technologies in renewable energy and sustainable materials, promoting economic growth and competitiveness and safeguarding citizens' health and wellbeing. For instance, regulations requiring more sustainable materials can encourage organizations to research and develop new, more sustainable materials that meet these requirements. However, the cost of implementing these measures or adopting new technologies and practices (without incentives or government support) may be expensive, and many companies may be reluctant to make the necessary investments unless they are confident that they will be able to recoup their costs over time, among other reasons. In some cases, these requirements may be seen as burdensome or unnecessary and may be resisted by those required to comply with them.

As per (vi), some organizations may be hesitant to implement Industry 4.0 technologies due to resistance to change from employees and other stakeholders. This can make it difficult for organizations to adopt and utilize these technologies fully. Resistance to change refers to the reluctance or refusal of individuals or groups to accept or adopt new ideas, technologies, or ways of doing things. In the context of Industry 4.0 and implementing new technologies in renewable energy and sustainable materials development, resistance to change can be a significant barrier. From varieties of studies and based on experiential factors, the expert panel posits that individuals or groups may resist change due to fear of the unknown and may be uncertainty about how the new technologies will affect their work or their roles within the organization; also, possibly due to skepticism about the value of the latest technologies or cost and effort required to implement them. Still, others may simply resist change for personal or cultural reasons. Overcoming resistance to change can be challenging and may involve educating employees and stakeholders about the benefits of the new technologies, addressing any concerns or fears they may have, and providing support and resources to help them adapt to the changes. Thus, stakeholders must change organizational policies, processes, and structures to support the implementation and adopt training programs, communication campaigns, and incentives to help employees embrace new technologies and practices.

Finally, in (vii), the adoption of Industry 4.0 technologies is still in its early stages. A limited pool of skilled workers is currently trained in the associated technologies, such as artificial intelligence, the Internet of Things, and 3D printing. This lack of qualified personnel challenges organizations looking to adopt and maintain these systems in the context of renewable energy and sustainable materials development. Despite the current challenges, there is optimism that the situation will improve due to increased global awareness and training and curriculum changes in higher education institutes, leading to more trained workers. The following section will explore different case examples and the outcomes of various Industry 4.0 technology applications, uncovering common threads and factors that may have contributed to their implementation.

4.3.2. Exploring industry 4.0 technologies on businesses of different sizes and sectors and how three energy case companies are benefiting from implementing these technologies

The renewable energy sector has seen numerous successful implementations of Industry 4.0 technologies and approaches [1]. One example is smart grids in Copenhagen, Denmark, which aims to become carbon neutral by 2025 [128]. As such, advanced sensors and control systems, as well as data analytics, have been implemented to increase the share of renewable energy in the power mix and improve the efficiency and reliability of the grid. Another example is the work of material scientists at the University of California, Berkeley, who have developed a data-driven approach to synthesizing sustainable materials using optimized chemical reactions [129, 130]. The EU-funded project "H2020-Factories of the Future" has also demonstrated the successful adoption of I4.0 technologies in producing renewable energy and sustainable materials, including using data analytics to optimize production processes [131]. Closed Loop Partners have funded several projects that use I4.0 technologies to improve the sustainability of materials production and use. One of them is Pivot Bio, a company that uses machine learning and IoT sensors to optimize the use of microbes as fertilizer replacements in agriculture [132]. Table 5 showcases different case companies employing Industry 4.0 technologies across various areas to promote sustainable business operations.

(i) Case A (D-GEEZ) is located in the North Sea off the coast of Germany and is a prime example of the role that I4.0 technologies and approaches can play in renewable energy and materials development. The wind farm, consisting of 80 wind turbines with a total capacity of 288 MW, was commissioned in 2014. It was the first offshore wind farm in the world to be fully equipped with an advanced condition monitoring system, which uses sensors and data analytics to monitor the performance of the wind turbines in real time and predict maintenance needs [133]. This has helped to increase the reliability and availability of the wind farm and reduce downtime and maintenance costs. In addition to using advanced monitoring and data analytics, Case A has implemented automation and digital twin technology at their wind farm. The company has developed a digital twin of the wind farm, which allows it to simulate and optimize the performance of the turbines and the grid connection. This has helped improve the wind farm's efficiency and stability, thereby contributing to developing a more sustainable and efficient renewable energy system.

Table 5
Case illustration of sustainable Akin companies leveraging industry 4.0 technologies.

	Company	I4.0 Technology	Application
1.	Intel www.intel.com	IoT sensors and other devices to collect data on the production and use of materials	To optimize the process and development of more sustainable products. Track the environmental impact of its supply chain and improve resource efficiency.
2.	Adidas www.adidas.com	3D printing and digital twinning technologies	To produce customized, complex parts with minimal material waste and to optimize its material production processes. To reduce resource consumption and waste generation and improve its material production's sustainability.
3.	DanTysk www.dantysk.com	Advanced sensors, predictive maintenance algorithms, and digital twins	To optimize the performance of the turbines and reduce downtime (achieved a 99.5% availability rate)
4.	Danfoss (Producers of energy-efficient HVAC) www.danfoss.com	Data analytics and machine learning	To optimize production and improve the energy efficiency of its products
5.	SolarCity (Solar panel manufacturer) www.solacity.com	Robotics and automation and a data-driven approach for operations optimization	To improve efficiency, reduce waste, and optimize its supply chain and energy consumption.
6.	Eskom (Electricity supplier) www.eskom.co.za	Sensors and data analytics for advanced monitoring and control systems for its coal-fired power plants	To optimize operation, increase the efficiency and reliability of the plants, and reduce waste and emissions.
7.	Tesla (Electric vehicles and renewable energy products) www.tesla.com	Robotics and automation	To improve efficiency and reduce waste, as well as integrating renewable energy sources into the factory's power supply
8.	Novozymes (biotech) www.novozymes.com	Data Analytics	To optimize the efficiency of its enzyme production and integrate renewable energy sources into its operations.
9.	SunPower (Solar panel manufacturer) www.sunpower.com	IoT sensors and other devices to collect data	To monitor the performance of its panels in real-time and identify potential issues before they occur
10.	Vestas (Wind turbine manufacturer) www.vestas.com	3D printing and data analytics, including Digital twin and IoT sensors to collect data	To simulate and optimize the performance, monitor the performance of its turbines in real-time and schedule maintenance as needed
11.	GE Renewable Energy www.ge.com	3D printing	To produce customized and complex parts and structures, reducing waste and increasing efficiency
12.	First Solar www.firstsolar.com	Data analytics and machine learning	To optimize its manufacturing processes and increase efficiency
13.	Sasol (Energy and chemical) www.saso.com	IoT sensors and other devices to collect data	To optimize the operational performance of its coal-to-liquids and gas-to-liquids plants to reduce waste and emissions
14.	Tata Steel plant www.tatasteel.com	Digital twin technology	To optimize the performance of its furnaces and reduce energy consumption
15.	Veolia Water Technologies plant www.mywater.veolia.us	Data analytics platform	To optimize the performance of its water treatment processes and reduce energy consumption cost savings, and improve sustainability
16.	Dangote Group www.dangote.com	IoT sensors and data analytics	To monitor the performance of the plants in real-time and optimize their operation, to increase the efficiency and reliability of the plants, as well as reduce waste and emissions
17.	Toyota Motor Corporation www.global.toyota.com	Data analytics and artificial intelligence (smart factory - sensors on machinery and equipment)	To monitor performance and detect any issues or adapt to changing production needs
28.	Novomer (Chemical manufacturing) www.novomer.com	Advanced process control and machine learning	To improve the efficiency of its chemical processes for producing sustainable polymers from renewable feedstocks

(ii) Case B (S-GECC) is a global energy and chemical company operating in South Africa and other countries. Case B's adoption of I4.0 technologies uses advanced monitoring and control systems for its coal-to-liquids and gas-to-liquids plants. These systems apply sensors and data analytics techniques to monitor the performance of the plants to optimize their operation. The company is also actively engaged in I4.0 for materials development, mainly the use of 3D printing for the development of valves for oil and gas pipelines. The valve, made of durable and corrosion-resistant material (Inconel 625), is produced faster, with less waste, and customized to each pipeline's specific needs. The company has established a dedicated 3D printing facility at its research and development center in South Africa, where it tests and optimizes various 3D printing processes and materials. Case B's adoption of 3D printing technology has revolutionized materials development in their oil and gas facility, increasing production efficiency by 20%. This new technology enables the creation of durable, customized, and corrosion-resistant components that can enhance the performance and sustainability of pipelines and other infrastructure. This is a prime example of the role of I4.0 technologies and approaches in developing sustainable materials. The company is also exploring using renewable energy sources like solar and wind power. The company has implemented advanced monitoring and control systems for these sources, allowing real-time monitoring and optimizing performance.

(iii) Case C (V-GMWT) is a leading global manufacturer of wind turbines and a pioneer in using I4.0 technologies and approaches in the renewable energy sector. One example of Vestas' adoption of I4.0 technologies is the use of data analytics and AI to optimize the performance of its wind turbines. The company has developed an online performance monitoring system that uses data from sensors on the turbines to identify patterns and trends and to predict when maintenance is needed. This has helped increase the turbines' availability and reliability and reduce downtime and maintenance costs. Vestas has also implemented automation and digital twin technology in its wind turbine manufacturing processes. The company has developed a digital twin of its blade manufacturing plant, which allows it to simulate and optimize the production process and identify and resolve bottlenecks. Another example of Case C's use of I4.0 technologies and approaches in materials development, mainly through 3D printing materials development, is the company's development of a 3D-printed blade for wind turbines. The edge, made of a lightweight and durable material called Graphene, has a longer lifespan and higher performance than traditional fiberglass blades. 3D printing technology has allowed Vestas to manufacture the edge faster and with less waste and customize it to the specific needs of each wind turbine. The company has established a dedicated 3D printing facility at its research and development center in Denmark, where it tests and optimizes various 3D printing processes and materials. The adoption of 3D printing technology by

Table 6
Addressing Challenges to Implement I4.0 Technologies for Clean Energy and Sustainable Materials through Economic, Regulatory, and Technical Strategic Planning.

Strategic Planning to Overcome the Challenges		Challenges to Implementing Industry 4.0 for Sustainable Push						
		High upfront costs	Limited availability of renewable energy and materials	Lack of standardization and interoperability	Cybersecurity risks	Stringent government requirements	Resistance to change	Lack of skilled workers.
Economic	Explore Grants	✓	✓	✗	✓	✓	✓	✗
	Secure Loans	✗	✓	✗	✓	✓	✓	✓
	Explore Public-Private Partnerships	✗	✓	✗	✓	✓	✗	✓
	Leverage on Internal Funds	✓	✓	✗	✓	✗	✓	✓
Regulatory	Identify Relevant Laws and Regulations	✗	✗	✓	✓	✓	✓	✓
	Develop a Regulatory Compliance Strategy	✗	✗	✓	✓	✓	✓	✓
	Ensure Smooth Rapport with Regulatory Agencies	✗	✗	✓	✓	✓	✓	✓
Technical	Understand Cloud Computing	✗	✓	✓	✓	✓	✓	✓
	Implement Cyber Security Strategies	✗	✓	✗	✓	✓	✓	✓
	Provide Training for Employees	✗	✓	✗	✓	✓	✗	✓

Vestas can revolutionize materials development in the renewable energy sector by enabling the production of lightweight, durable, and customized components that can improve the performance and sustainability of wind turbines as renewable energy systems

4.3.3. Ameliorating the adoption of I4.0 for renewable energy and sustainable materials solutions through economic, regulatory, and technical strategic planning

The study presents best practices and strategic guidance to help practitioners, following the case of the multinational energy companies and organizations involved in renewable energy and sustainable materials development, to effectively design and implement Industry 4.0 technologies and approaches in their operations. Table 6 illustrates practical strategies to ensure the integration of IoT, AI, and other business and operations management technologies to increase efficiency and productivity and support Clean Energy and Sustainable Materials, thus addressing economic, regulatory, and technical challenges. The figure also highlights the methods for overcoming economic, regulatory, and technical challenges.

According to a source, a company can secure funding for renewable energy and sustainable materials development projects by applying for grants from government agencies or private organizations. The process may include researching and identifying funding opportunities, developing a proposal outlining the project's objectives, benefits, and costs, and submitting it to the funding agency or organization. Alternatively, the company can secure loans or other financings from financial institutions that fund renewable energy and sustainable materials development projects. This can be done by identifying and approaching suitable financial institutions and providing them with financial information, such as financial statements and projections, to demonstrate the company's creditworthiness and ability to repay the loan. Additionally, the company can explore public-private partnerships. It could partner with other organizations to share the implementation costs by identifying organizations with complementary expertise, resources, or objectives and developing a mutually beneficial collaboration to implement I4.0 technologies. This approach will help the company to access additional funding and resources to support the implementation of the project. Lastly, a prospective company can leverage internal funds or reallocate the budget from other areas of the business to support the implementation of Industry 4.0 technologies by identifying available resources within the company and redirecting them towards implementing I4.0 technologies. This may require the company to change its budget and resource allocation plans and prioritize the implementation of I4.0 technologies over other initiatives.

To ensure compliance with all relevant laws and regulations related to I4.0 technologies and sustainable materials development, a company must thoroughly review the applicable laws and regulations, develop a regulatory compliance strategy, and establish a strong relationship with regulatory agencies and other stakeholders. The review process involves researching and identifying all of the laws and regulations that apply to the company's operations, such as environmental regulations, labor laws, and data privacy laws. By understanding these laws and regulations, the company can ensure that its operations comply and are not at risk of penalties or fines. Additionally, the company needs to develop a regulatory compliance strategy outlining the specific steps to ensure compliance. Thus, implementing internal policies and procedures, training employees on relevant laws and regulations, and appointing a compliance officer should be regularly reviewed and updated to reflect any changes in the regulatory environment. Such laws and regulations should be periodically reviewed and updated to reflect any changes in the regulatory environment. At the same time, the compliance officer continues to build a strong relationship with regulatory agencies and other stakeholders to stay informed of any changes to the regulatory environment and to ensure that the company's interests are considered in any new regulations or policies. This involves building and maintaining regular communication with regulatory agencies and other stakeholders, such as industry associations and local communities, and participating in relevant industry associations or regulatory committees to have a voice in shaping regulations and policies that affect the industry.

Investing in advanced data integration and management systems, developing a robust cybersecurity strategy, establishing a solid relationship with cybersecurity experts and conducting regular security audits and testing, and providing training for employees on best practices for protecting data and systems from cyber threats are all crucial steps to ensure that a company can effectively integrate and analyze data from Industry 4.0 technologies, optimize performance and reduce downtime, protect data and systems from cyber threats, identify and address potential vulnerabilities and ensure the company's overall cybersecurity posture. To ensure successful integration and analysis of data from Industry 4.0 technologies, as well as optimized performance and protection from cyber threats, a company must invest in advanced data integration and management systems, develop a comprehensive cybersecurity strategy, collaborate with cybersecurity experts, and provide regular security audits and testing, as well as training for employees on best practices for protecting data and systems. A company can identify and address potential vulnerabilities and ensure its overall cybersecurity posture by taking these steps. Cybersecurity experts can help identify and address vulnerabilities, and regular testing and auditing can ensure that the company's cybersecurity measures are up-to-date and effective. Employee training on security protocols, such as password management, safe internet browsing, properly handling sensitive data, and awareness of potential risks associated with cyber threats, can also improve overall cybersecurity posture.

5. Discussion

5.1. Comparison of findings

The literature review has revealed that, despite the progress of I4.0, there is still a wide gap in knowledge regarding how this process can be operationalized and scaled up, especially in driving renewable energy and sustainable materials. This is evidenced by the low adoption of this concept, even though it is a viable business solution. The financial risks associated with I4.0 technologies are high due to the costly development and integration of new technologies, the maintenance and securing of existing systems, and the need for knowledgeable personnel to manage them. Regulatory issues may include complying with environmental regulations, safety and health standards, and harmonized laws and regulations across different countries. Technical barriers include the limited availability of renewable energy materials, a lack of standardization and interoperability, cybersecurity risks, and stringent government requirements. Additionally, there is resistance to change due to unfamiliarity with the technology and its implications and long-term sustainability issues due to the need for ongoing maintenance and upgrades.

The potential rewards of adopting Industry 4.0 technologies must be carefully weighed against their associated risks. These rewards include increased efficiency and productivity, improved safety and security, better customer service, and new business opportunities. Consequently, while the adoption of blockchain and augmented reality did not help the D-GEEZ, S-GECC, and V-GMWT organizations address any of the challenges related to economic (financial) risks, regulatory issues, and technical barriers, the overall benefits of Industry 4.0 technology still provide great potential for companies looking to remain competitive in the 21st century. The potential rewards of I4.0 technology far outweigh the risks, making it an attractive option for businesses seeking to maximize their potential in the modern marketplace.

As per the expert from the S-GECC case, the company’s utilization of IoT, Big Data, 3D printing, and Data and Analytics has enabled them to address customer needs, decrease product development times, and launch new and original products. Therefore, S-GECC aims to enhance its renewable energy portfolio, reduce its carbon footprint and enhance efficiency, productivity, and sustainability in its operations by applying Industry 4.0 technologies and approaches. An illustration of this approach is when an S-GECC respondent was asked about their strategic approach toward implementing Industry 4.0. They responded that they had conducted a comprehensive analysis of the current processes and infrastructure and found several areas where one could apply Industry 4.0. They did this by involving a multidisciplinary team, including experts in renewable energy, sustainable materials, advanced manufacturing, and information technology. The team then devised a strategy to integrate IoT technologies for real-time monitoring and control of their renewable energy operations, investing in advanced analytics, AI technologies, and experts to optimize performance and reduce downtime and maintenance costs.

Additionally, these technologies have enabled the S-GECC case company to bolster its supply chain efficiency, cut production costs and resources, and incorporate real-time customer feedback into product optimization. Importantly, Industry 4.0 technologies continue to provide the company with competitive advantages and the ability to keep up with the ever-changing demands of customers and the global markets. In the D-GEEZ, S-GECC, and V-GMWT cases, advanced sensor and cloud technologies were identified as potential solutions for data analytics and integration, capable of connecting data collected through IoT technologies to other data sources or storage. Additionally, AI and big data technologies were identified in V-GMWT specifically, with AI providing forecasting capabilities and optimizing operations.

It can be concluded from the alignment analysis between the perspectives of Industry 4.0 experts on the latest adoptions and existing literature on renewable energy and sustainable materials development that, generally, all data sources have a reasonable correlation. Our research suggests combining IoT, Big Data and Analytics, AI, Blockchains, VR, and Rapid Prototyping can significantly promote clean energy and energy-related materials. Additionally, educating stakeholders on the benefits of digitizing operations strategies could motivate sustainable practices and significantly impact energy management and costs. Notwithstanding, companies may face several substantial obstacles that need to be prepared for, such as high start-up costs, limited availability of renewable energy resources, lack of standardization and interoperability, cybersecurity threats, government regulations, variability, and lack of skilled labor, which the consulted experts highlighted. This finding reinforces previous academic studies on integrating Industry 4.0 with sustainability.

We have a high confidence level in the reliability, validity, and ethical soundness of the data collected in this study. However, it is important to note that the findings presented in this study may be subjective and biased based on the opinions of individuals or the specific case being studied. Moreover, future researchers must consider the context of this research and acknowledge that the results may not be applicable in different situations or scenarios. The lack of research on cloud computing and digital twining, both in academic literature and among practitioners’ insights on practical applications, is evident. Thus, further research is needed to explore the potential of these technologies in various industries and to understand the challenges that may arise during their implementation. Additionally, future studies could consider offering participation incentives to increase the sample size and diversity of participants.

5.2. Theoretical and practical. Implications

This study enhances the theoretical understanding of I4.0 and its implications for renewable energy and materials development. It presents a conceptual framework highlighting the potential of renewable energies and materials within the context of Industry 4.0, offering insights into their adoption and implementation in the industrial sector. Furthermore, identifying critical challenges associated with Industry 4.0 applications for sustainable energy materials and renewable energy systems contributes to the theoretical knowledge base in this field. This study provides practical insights into applying I4.0 technologies, including IoT, AI, and advanced manufacturing, to enhance efficiency, productivity, and sustainability in the renewable energy and materials sectors. It offers potential solutions to address economic, regulatory, and technical barriers, guiding organizations in overcoming obstacles while adopting I4.0 technologies. The findings of this study are valuable for students, researchers, scholars, and practitioners, serving as a reliable reference for designing and implementing I4.0 strategies in the renewable energy and materials domain. Moreover, the study supports the transition towards a sustainable and low-carbon future by highlighting the practical benefits and challenges of I4.0 technologies in the renewable energy and materials sectors.

6. Conclusion

6.1. Insights

In conclusion, the study finds that I4.0 technologies and practices have the potential to facilitate the advancement and deployment of renewable energy and sustainable materials through real-time data collection, analysis, and decision-making, as well as the development of new products and services. However, various significant hurdles hinder the widespread adoption of these technologies in the renewable energy and materials sectors, including technical, economic, and regulatory barriers. Therefore, the study investigates ways that Industry 4.0 technologies such as the IoT, AI, and advanced manufacturing techniques can enhance efficiency, productivity, and sustainability in these sectors. It also presents potential solutions for overcoming technical, economic, and regulatory challenges during implementation. It provides a comprehensive understanding of the present knowledge, key factors, and opportunities associated with I4.0 in renewable energy and materials development.

Moreover, this report emphasizes the importance of I4.0 technologies and their potential implications for renewable energy management and materials development. By presenting a clear research objective, a well-defined methodology, transdisciplinary approaches, and case studies, this report offers depth and credibility to the study. It serves as a teaching and curriculum development guide and a reference for research projects and coursework. Additionally, the report thoroughly overviews critical concepts and concerns associated with Industry 4.0 implementation within the renewable energy and materials development realm.

6.2. Limitations and outlook

The present study has a limited scope, focusing specifically on the implications of I4.0 implementation for renewable energy management and materials development. This narrow focus may result in overlooking other aspects and applications of I4.0 in different sectors or industries. The literature review is also confined to studies published within a specific timeframe, which may exclude recent advancements and developments in the field.

It is important to acknowledge the potential influence of bias and subjectivity in the findings and conclusions of the paper. Different researchers and selected case studies may introduce varying perspectives and contexts, leading to different interpretations and conclusions.

The paper highlights the lack of standardization and interoperability as significant challenge in implementing I4.0 technologies. To facilitate the seamless integration of renewable energy and materials development, future research should explore potential solutions and best practices for addressing this issue.

There is limited research on cloud computing and digital twinning within the context of I4.0, as highlighted by the review paper. Future studies should explore the potential of these technologies and their role in enhancing efficiency, productivity, and sustainability in the renewable energy and materials sectors.

The review paper acknowledges the need for larger sample sizes and diverse participants in future research. Increasing the sample size and gathering insights from a wider range of stakeholders, including industry practitioners and policymakers, can provide a more comprehensive understanding of the topic.

Furthermore, the review paper briefly mentions long-term sustainability issues associated with I4.0, such as ongoing maintenance and upgrades. Future research should delve deeper into the environmental and socio-economic implications of I4.0 technologies to ensure their long-term sustainability and positive impact.

Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

Declaration of competing interest

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.

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