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Industry 5.0 and SDG 9: a symbiotic dance towards sustainable transformation

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Abstract

The convergence of Industry 5.0 (I5.0) and Sustainable Development Goal 9 (SDG 9) signifies a transformative shift in global industries, propelled by a new triple bottom line approach– human-centric, sustainable, and resilient. Departing from traditional models, I5.0, an evolution from Industry 4.0, strategically aligns with SDG 9 to reshape industrial landscapes and promote global sustainable, resilient, and inclusive development.

I5.0's emphasis on resource optimization and collaboration between humans and machines marks a departure from technologically driven manufacturing (I4.0), ushering in a sustainable production model. Cutting-edge technologies, including Artificial Intelligence (AI), Machine Learning (ML), and automation, optimize resource utilization, enhancing operational efficiency to support sustainability goals. Yet, challenges like initial implementation costs and a lack of global sustainability standards pose obstacles.

The human-centric integration within I5.0 prioritizes human needs throughout the manufacturing process. Collaborations with Cobots and AI-ML technologies optimize workflows, contribute to customization, and align with SDG 9's vision, necessitating robust training programs and strategic considerations for workforce adaptation and financial investments.

Exploring I5.0 resilience within SDG 9 unveils its pivotal role during crises, such as the COVID-19 pandemic. Discussions navigate challenges related to supply chain disruptions, economic impacts, and geopolitical factors, emphasizing the need for strategic resilience, sustainability, and human-centric approaches. I5.0 resilience, guided by Cobots, aligns with SDG 9's focus on resilient infrastructure.

Sustainable Business Model Innovation (SBMI) emerges as a central point of contention in the I5.0 and SDG 9 interplay. Advocates tout its transformative potential for sustainability goals, while skeptics question scalability and adaptability, reflecting the complexity of factors in achieving sustainable and resilient industrial development.

Therefore, the strategic imperative of I5.0 and SDG 9 unfolds as a transformative force for positive change, embedded in SBMI. This collaborative journey transcends the confines of a production system, ushering in a future where technology management, supported by SBMI, proactively reinforces resilience, societal well-being, and environmental stewardship. The future of I5.0 raises questions about innovative ecosystems, collaboration practices, geopolitical impacts, circular production models, and extending I5.0 beyond current geographical limits.

Keywords Industry 5.0 (I5.0), Sustainable development goal 9 (SDG 9), Human-centric, Resilient, Sustainable, Cutting-Edge technologies (AI, ML, IoT, Robotics), Sustainable business Model Innovation (SBMI), Supply Chain

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Background

The intricate interplay between Industry 5.0 (I5.0) [1, 2] and Sustainable Development Goal 9 (SDG 9) - a set of 17 global goals that were adopted by all United Nations Member States in 2015 as part of the 2030 Agenda for Sustainable Development- extends beyond being merely a transformative force [3, 4] encapsulated in a strategic imperative to promote positive change. Serving as an extension of the digital industrial revolution, I5.0 aims to transcend conventional technical processes by revolutionizing industries to address contemporary human and environmental aspects through a new approach that, from the perspective of the European Union (EU), reflects a new triple bottom line dimension– human-centric, sustainable, and resilient– means a substantial departure from traditional models [1, 2].

The definition of I5.0 is currently evolving, lacking a detailed and widely accepted definition in the literature [5]. Numerous attempts have been made to refine the preliminary definition [6] consolidating some of these efforts. Essentially, these endeavors aim to enhance the initial concept of I5.0, acknowledging the industry's potential to contribute to societal goals beyond employment and economic growth. According to Müller (2020) [7], I5.0 'recognizes the power of the industry to achieve societal goals beyond jobs and growth, aiming to become a provider of prosperity. This involves making production respect the boundaries of our planet and placing the well-being of the industry worker at the center of the production process.'

Despite being in its early stages, tangible examples exist to illustrate the principles and applications of I5.0. One such example is the concept of digital twins—virtual replicas of physical objects embedded with sensors for simulations and scenarios. Digital twins can simulate entire automation systems or specific components, serving as a versatile tool for virtual testing of work processes and products, including the measurement of social and environmental impacts through simulations [8]. Another example lies in the aviation industry's use of IoT sensors to monitor aircraft components in real time, tracking factors like engine performance and fuel efficiency. Predictive maintenance based on this IoT data helps prevent unexpected failures, ultimately reducing downtime [9].

The success of this symbiotic relationship hinges on several factors, which serve as pivotal milestones in anchoring these industrial shifts. This collaborative effort not only reshapes industrial landscapes but strategically aligns with the vision of global sustainable, resilient, and inclusive development outlined in SDG 9, marking a paradigm shift driven by strategic foresight of development [2, 10].

SDG 9 has dynamically guided significant technological advancements during the transition from Industry 4.0 (I4.0) to the emergence of I5.0, acknowledging the strategic importance of this evolution [2, 3, 11]. Consequently, this paradigmatic shift underscores the fundamental role of I5.0 in reshaping the industrial landscape, strategically aligning with the holistic development vision outlined in SDG 9 [2, 10].

One sensitive aspect of technological advancements in I4.0 was the concern about job losses. Reliable global statistics on the number of jobs lost due to I4.0 and the potential job recovery with the adoption of I5.0 are not yet available. Early studies associated I4.0 with worker substitution and increased unemployment, while subsequent scholars have contested the belief that I4.0 will significantly reduce employment. Some argue that it might even result in more industrial employment [12]. Consequently, there is inconclusiveness regarding the employment-related effects of I4.0, with most publications discussing theoretical assumptions rather than providing empirical evidence on actual changes [12]. However, the focus of I5.0 on human-centric principles suggests a belief in greater human participation in production. This emphasis could potentially lead to the recovery of jobs lost during the transition from I4.0, although this remains a speculative proposition.

At the heart of I5.0 is human-centric innovation, strategically emphasizing collaboration between humans and machines to foster a symbiotic relationship that enhances productivity and creativity [2]. This strategic alignment seamlessly resonates with SDG 9's inclusive goals, ensuring equitable benefits and strategic infrastructure development. The intersection of I5.0 and SDG 9 serves as a powerhouse for transformative change, strategically fostering innovation, inclusivity, and sustainable industrialization [10].

Sustainable technologies and innovative approaches, integral to I5.0, play a pivotal role in achieving SDG 9's objectives. Cutting-edge technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Machine Learning (ML) and advanced robotics associated with sustainable mechanisms such as the circular and shared economy strategically optimize the use of resources and significantly contribute to the construction of resilient infrastructures [3]. The principles of I5.0 seamlessly align with SDG 9's vision of efficient, sustainable development.

Addressing challenges from a strategic perspective, I5.0 ensures diverse empowerment and responsible innovation [10]. The strategic human-centric focus not only adapts to but proactively shapes ethical considerations in the use of cutting-edge technologies like AI [13]. Ensuring alignment with sustainability and inclusivity principles embedded in SDG 9 is strategically paramount, driven by an industry actively seeking positive and transformative impact.

One of the pivotal factors influencing the successful development of I5.0 is Sustainable Business Model Innovation (SBMI), which plays a crucial role in its interaction with SDG 9. This interaction is essential for constructing resilient infrastructures, promoting sustainable industrialization, and transforming human-machine interaction into socio-economic and environmental gains [3].

Therefore, the strategic imperative of I5.0 and SDG 9 unleashes a transformative force for positive change. This collaboration, strategically grounded in the change of the production system, not only advances industrial capabilities but strategically ushers in a future where the management of technology– encapsulated by Business Model Innovation (BMI)– and not the technology itself, becomes a proactive and positive force for ensuring resilience, societal well-being, and environmental stewardship.

Achieving sustainability and environmental friendliness in the landscape of I5.0: a comprehensive exploration

The ascent of I5.0 marks a transformative era in sustainable industrial practices, emphasizing resource optimization and the symbiotic collaboration between humans and machines. This paradigm underscores the imperative to design products and processes aligned with environmental concerns [14], conserve power system [15], and reduce rubbish [14]. This holistic approach encompasses decreased energy consumption by the industrial system [16], improved efficiency in resource utilization [17], and reduced waste generation by the production system [14], signifying a shift from a technologically driven manufacturing focus (I4.0) to a more sustainable production model [2].

The hallmark of I5.0, benefiting from innovation in human-machine interaction, is supported by pioneering BMI aligned with sustainability imperatives, emphasizing lean production to minimize resource disposal and overproduction [14]. Additionally, I5.0 has the potential to enhance economic sustainability by advocating for local manufacturing, aligning production processes with local demands, and mitigating adverse impacts from global supply chains [18].

The impact of I5.0 extends deeply into industry environments, necessitating a comprehensive policy framework. These policies are vital for ensuring (a) a regulated environment addressing ethical considerations in cutting-edge technology use, (b) robust data governance covering aspects like ownership, sharing, and security against unauthorized access, (c) standardization to promote the development and adoption of industry standards, (d) initiatives supporting education and workforce development to equip individuals with the skills demanded by the evolving landscape of I5.0, (e) incentives for research and development (R&D), (f) cybersecurity policies addressing concerns tied to increased connectivity, (g) an innovation-friendly environment fostering international collaboration, (h) consumer protection policies dealing with product safety, quality, and information transparency, and (i) sustainable practices emphasizing minimal waste generation, efficient resource management, and transformative shifts in business models [2, 6, 14, 19–21].

To augment sustainability, I5.0 harnesses cutting-edge technologies, particularly AI, to optimize resource utilization. The integration of smart and connected machines, ML, and industrial automation facilitates real-time forecasting of production efficiency [2, 14, 21]. This forecasting, grounded in ongoing activities, empowers the industry to dynamically adjust processes, averting losses and enhancing overall operational efficiency. For example, BMW's iFACTORY commitment to sustainable production extends beyond technical deployment to include eco-friendly materials, renewable energy sources, and a strong emphasis on recycling. The integration of intelligent machines and ML has been instrumental in fortifying BMW's sustainability endeavors, upholding rigorous standards of quality and efficiency in manufacturing processes [22].

However, the journey toward sustainable practices in I5.0 presents notable challenges. Initial implementation costs, particularly burdensome for smaller enterprises, pose financial impediments [23]. Additionally, the absence of a global standard for sustainability practices and engagement is pivotal for ensuring comprehensive and consistent adoption across diverse industries and regions [24].

The perpetual balancing act between economic growth and sustainability objectives takes center stage, necessitating meticulous evaluation of associated costs and benefits. This evaluation is crucial for achieving a harmonious integration of sustainable practices within the industrial landscape, especially given uncertainties arising from high energy costs due to armed conflicts and geopolitical issues. For instance, global coal consumption reached a new all-time high in 2022 [25], resulting in volatile and high-power prices. Furthermore, geopolitical rivalry can block the supply of raw materials necessary for expanding renewable sources, particularly solar and wind sources. From the EU's perspective, most of the raw materials used in clean technologies originate from regions beyond its territorial boundaries: 98% rare earth element is from China; 98% of borate is from Türkiye; 93% of ruthenium, 92% of iridium, 80% of rhodium and 71% of platinum supplies currently come from South Africa, and 85% of the niobium it consumes from Brazil [26].

In adopting a critical lens, this exploration contributes to a more comprehensive understanding of the dynamic

nexus between I5.0 and SDG 9, fostering a balanced and informed perspective on the journey toward sustainable practices in the industrial landscape.

Human-centric integration within the dynamic nexus of I5.0 and SDG 9

The human-centric perspective embedded within I5.0 goes beyond being a mere technological shift; it represents a strategic imperative for societal and environmental transformation [14]. This perspective seamlessly aligns with SDG 9 and the broader global development agenda.

In this paradigm, the central theme is the prioritization of human needs throughout the manufacturing process, reflecting a commitment to inclusivity and equity [19]. I5.0, as an evolution from I4.0, strives to move beyond traditional technologic-centric manufacturing. It emphasizes a collaborative approach where technology serves humanity, aligning harmoniously with the goals of SDG 9– envisioning resilient infrastructure, inclusive industrialization, and fostering innovation.

A fundamental tenet of this integration is the enhancement of human efficiency and productivity, achieved using advanced technologies to reintegrate individuals into the core of the production process. Collaborative robots, known as Cobots, exemplify this symbiotic relationship by handling repetitive and hazardous tasks. This allows human workers to engage in creative pursuits and strategic decision-making [27, 28]. This human-machine collaboration serves not only to optimize workflows but also as a catalyst for customization, ensuring end-user experiences align with societal needs and preferences [19, 21]. For instance, major automotive manufacturers like Audi and Volkswagen propose 'intelligent factories' to enhance production flexibility through improved human-robot interaction [29].

Furthermore, the integration of I5.0 technologies with well-trained professionals acts as a catalyst for production optimization and innovation. This collaboration addresses not only efficiency concerns, but also bridges the gap between production and consumption. It empowers employees to deliver additional value to customers promptly [19, 21, 30]. Illustratively, the incorporation of technologies such as AI-ML aligns with SDG 9's vision by shortening the production-consumption cycle [31]. This contributes to increased business efficiency and supports sustainable development.

However, this integration is not without its challenges. As the workforce adapts to super robots, intelligent equipment, and interconnected technologies, the need for robust training programs becomes imperative to ensure seamless collaboration between humans and machines [32]. Educational initiatives must focus not only on technical skills but also encompass the ethical considerations and societal impacts of these advancements.

Moreover, I5.0 demands substantial financial investments, covering not only technology but also human-centric training initiatives– a significant challenge for I5.0 [13]. This challenge is particularly pronounced for the EU, where the working-age population is projected to decrease from 64 to 44% of the total population by 2060 [33].

Therefore, the human-centric perspective within I5.0, viewed in the dynamic nexus with SDG 9, emerges as a potent force for change. The strategic alignment of technological innovation with human needs fosters resilience in industrial processes and actively contributes to global sustainable and inclusive development goals.

The dynamics of I5.0 resilience: a holistic exploration in the context of SDG 9

In the evolving landscape of I5.0, transitioning from a focus on efficiency to resilience becomes pivotal. This shift not only strengthens resilience but also aligns with the core principles of SDG 9– Industry, Innovation, and Infrastructure [2, 3]. This exploration delves into the multifaceted dynamics of I5.0 resilience, emphasizing its intricate connection with SDG 9, and addressing synergies and trade-offs in the continually changing global environment.

Amid the challenges posed by the COVID-19 pandemic, several sectors and countries demonstrated resilience through noteworthy instances. Examples include the transition to virtual healthcare, the robustness of the education sector via virtual platforms, organizations from different sectors adopting home office systems, and the steadfastness exhibited by the food, logistics, and energy industry [34]. These instances not only underscore socio-technical system (STS) adaptation but also serve as valuable indicators for I5.0 to enhance its support for SDG 9's vision of a robust and inclusive industrial infrastructure.

To comprehensively address these challenges, it is imperative to consider the risks of production disruption due to pandemics, climate change-induced catastrophes, and geopolitical rivalry. This consideration aligns with SDG 9's imperative for resilient infrastructure [35]. Events like the Fukushima disaster, Hurricane Katrina, and geopolitical conflicts in Eastern Europe and West Asia emphasize the vulnerabilities inherent in global supply chains [35]. The looming threat of China's dominance in rare earths further emphasizes the need for diversified strategies [36].

Critical factors, such as supply chain disruptions and economic impacts, demand careful consideration. Subsequent discussions delve into the repercussions of these challenges on supply chains, price volatility, and

production costs [37]. Commercial tensions and geopolitical conflicts emerge as potential disruptors, diverting resources from innovation toward military pursuits, posing a risk to global industries [38]. Urgent measures are advocated by critics, emphasizing strategic resilience and diverse approaches to ensure the robustness of I5.0 in an ever-evolving environment [39].

Within this context, the discourse shifts to the centrality of human-centricity and Cobots [40] as key factors for I5.0 resilience, aligning with the principles of SDG 9. Proponents emphasize the significance of human-centricity in the I5.0 landscape, positioning Cobots as the linchpin for the seamless merger of human craftsmanship with technological precision [40].

Moreover, the debate unfolds to explore I5.0's potential in bolstering climate resilience through technology, aligning with SDG 9's focus on sustainable and resilient infrastructure [2, 3]. Real-time predictive information, facilitated by smart sensors and customized software, emerges as a proactive measure against climate-related disruptions [34]. While advocates applaud these technological strides for their role in averting risks, critics raise questions regarding the scalability and accessibility of such solutions [41, 42].

In considering the dynamics of I5.0's response to challenges— embracing agility, technological capacity, and its interface with SDG 9– concerns related to pandemic risk, environmental challenges, and geopolitical threats come to the forefront. The need for a delicate balance between strategic resilience, sustainability, and human-centric approaches emerges as the quintessential consideration for the triumph of I5.0 in an unpredictable global scenario.

Navigating the interplay: SBMI in I5.0 and its impact on SDG 9

In the ongoing discourse surrounding the interplay between I5.0 and SDG 9, the role of SBMI becomes a central point of contention. Advocates assert that SBMI is indispensable, serving as the catalyst needed to propel industries into the next phase of evolution [17, 43–45]. Their argument revolves around the notion that reshaping operations for efficiency and sustainability aligns seamlessly with the goals of I5.0, contributing significantly to the pursuit of SDG 9. Proponents highlight the inclusive nature of SBMI, emphasizing that the benefits of technological advancements must reach a broader demographic, aligning with the social dimension of SDG 9 [46].

Furthermore, the integration of cutting-edge technologies, a characteristic of innovation that transforms the BMs, is hailed as instrumental in developing resilient and technologically advanced industrial infrastructure– a cornerstone of SDG 9 [44]. This strategic incorporation of advanced technologies, such as AI-ML, IoT, and robotics, not only enhances operational efficiency, but also contributes to establishing robust, adaptive industrial systems that drive the innovation and transformation of BMs [21]. This technological integration is considered pivotal for achieving the objectives outlined in SDG 9, particularly in building resilient infrastructure capable of withstanding environmental challenges and contributing to sustainable industrialization.

On the contrary, skeptics raise doubts about the transformative potential of SBMI, expressing concerns about its scalability and adaptability. They argue that, while certain BMs may contribute to sustainability, the overall impact on achieving SDG 9 remains uncertain [47, 48]. Skeptics highlight potential challenges related to the scalability of SBMI across diverse industries and question their adaptability to varying socio-economic contexts [49]. The debate unfolds at the nexus of human-technical interaction, sustainable development, and the imperative for resilient industrial infrastructure, with the role of SBMI revealing its relevance in the formation of this intricate interaction.

Therefore, the multifaceted discussion around SBMI in the context of I5.0 and SDG 9 encompasses both enthusiastic support and skepticism, reflecting the complexity of factors involved in achieving sustainable and resilient industrial development. As this debate delves into the intricacies of this dialogue, it aims to contribute valuable insights to the broader discourse on the convergence of Industry 5.0 and Sustainable Development Goals from the perspective of sustainable production system.

Conclusions

In the intricate dance between I5.0 and SDG 9, a transformative force emerges, weaving together technical evolution and a commitment to humanity, sustainability, and resilience. Beyond a mere upgrade, I5.0 embodies a paradigm shift, embracing a new triple bottom line approach that is human-centric, sustainable, and resilient, charting a course towards a future of positive change.

At its core, this synergy places SBMI as guiding milestones, anchoring shifts in the industrial landscape and strategically aligning with the vision of global sustainable, resilient, and inclusive development articulated in SDG 9.

The transition from I4.0 to I5.0 is not just a leap in technology; it signifies a profound shift marked by human-centric innovation. The collaboration between humans and machines, a defining feature of I5.0, emphasizes a symbiotic relationship that fosters not only productivity and creativity but also inclusivity. This strategic alignment resonates seamlessly with SDG 9, ensuring that benefits are equitably distributed, and infrastructure development is inclusive.

Sustainable mechanisms and technologies, integral to the DNA of I5.0, play a pivotal role in achieving SDG 9's objectives. From the IoT to AI-ML and advanced robotics, these technologies optimize resource utilization and significantly contribute to the development of resilient infrastructure and SBMI. The principles of I5.0 align harmoniously with SDG 9's vision of efficient and sustainable development.

In addressing challenges, I5.0 takes a strategic approach, ensuring diverse empowerment and responsible innovation. The human-centric focus not only adapts to ethical considerations in the use of cutting-edge technologies, but actively shapes them. This strategic alignment with sustainability and inclusivity principles embedded in SDG 9 is paramount, signaling an industry actively seeking positive and transformative impact.

As we navigate the profound changes brought about by the strategic imperative of I5.0 and SDG 9, it becomes evident that this journey goes beyond the limitations of a production system, raising numerous questions with only a few clear answers: Will I5.0 usher in an innovative ecosystem? Will it introduce new practices and collaborations? Will it pave the way for SBMI and establish a compelling value proposition for stakeholders at the local, regional, national, and global levels? How might geopolitical factors impact the development of I5.0 within the context of SDGs? Can I5.0 contribute to the promotion of circular production and consumption models, as well as the efficient utilization of natural resources? Is it possible to expand I5.0 beyond its current geographical boundaries?

Therefore, as with any complex problem, there are no quick fixes or simple single solutions. What seems reasonable to admit is that the future of I5.0 heralds a future where the management of technology– and not the technology itself– encompassed by SBMI, becomes a proactive and positive force to reinforce resilience, societal well-being, and environmental stewardship. In advancing industrial capabilities, I5.0 places emphasis on managing technology for a sustainable and inclusive global future, embodying the essence of human-centric, sustainable, and resilient progress.

Abbreviations

AI	Artificial Intelligence
BM	Business Model
EU	European Union
I4.0	Industry 4.0
I5.0	Industry 5.0
IoT	Internet of Things
ML	Machine Learning
SBM	Sustainable Business Model
SBMI	Sustainable Business Model Innovation
SDG 9	Sustainable Development Goal 9
STS	Socio-Technical System

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Author contributions
I am the sole author of this manuscript, responsible for the conception, design, analysis, and drafting of the manuscript. This work represents my original research, and I take full responsibility for its content. I declare that this manuscript has not been submitted elsewhere for publication.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Competing interests
The authors declare no competing interests.

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