

Technology, Sustainability, And Carbon Reduction: A Structured Review Of Digital Infrastructure, Industrial Robotics, And Additive–Subtractive Manufacturing

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ABSTRACT

Digital infrastructure, industrial robotics and additive–subtractive manufacturing are often treated separately, and rapid technology progress is changing the outlook for industrial decarbonization. This structured review combines these nine focal studies with 21 supporting studies to synthesize evidence for the carbon emission reduction potential of each of these three technology domains, the contextual variables that influence impact, and the key research gaps. All three domains of evidence point to three common decarbonisation pathways – better energy efficiency, green technological innovation and more efficient resource and factor allocation. Digital infrastructure is based on real-time monitoring and spatial spillovers between cities; industrial robotics on increased productivity, cleaner energy use and upgrading of global value chains; and additive–subtractive manufacturing on material efficiency and reduced machining with integrated systems reported to reduce the carbon footprint by as much as 80% compared to conventional milling. The size of these impacts is always qualified by a regional development and governance component and an energy-rebound effect that dampens but does not negate the impact. The key message of the review is that while all three technologies share a decarbonization logic, none of the reviewed studies addresses the combined deployment of the technologies – the deployment of integrated technology systems is the largest open question for future research.

Keywords: industrial decarbonization; digital infrastructure; industrial robots; additive manufacturing; carbon emissions

ABBREVIATIONS

Abbreviation	Meaning
2SLS	Two-stage least squares
AI	Artificial intelligence
AM	Additive manufacturing
ASIHM	Additive–subtractive integrated hybrid manufacturing
CEEM	Carbon-emission efficiency of manufacturing
CEI	Carbon-emission intensity
CI	Carbon intensity
CO ₂ / CO ₂ e	Carbon dioxide / carbon dioxide equivalent
DEA	Data envelopment analysis
DED	Directed energy deposition
GHG	Greenhouse gas
GTI	Green technological innovation
GVC	Global value chain
HM	Hybrid manufacturing
IIoT	Industrial Internet of Things
LCA	Life-cycle assessment
PBF	Powder bed fusion
PC	Per capita carbon emissions
SDG	Sustainable Development Goal

SEPRCE	Synergistic effect of pollution and carbon-emission reduction (term used by Han et al., 2024)
SM	Subtractive manufacturing
TC	Total carbon emissions
TFP	Total factor productivity
WAAM	Wire arc additive manufacturing

INTRODUCTION

The decarbonisation of energy systems is one of the key challenges of our time, and emerging technologies provide additional opportunities for transitioning towards a sustainable industry. Carbon dioxide (CO₂) is the biggest source of greenhouse-gas (GHG) emissions globally and it is produced primarily due to human activity (IPCC, 2022). Global carbon emissions rose by 6% in 2021 to about 36.3 GtCO₂e, of which China accounted for 12.04 GtCO₂e (International Energy Agency [IEA], 2022). Manufacturing energy use in China increased by 2.32 times, and carbon emissions increased by 2.26 times between 2000 and 2019 (Wang, Yu, & Sun, 2024). In this context, research on industrial decarbonization has significantly increased in recent years.

The shift towards sustainable manufacturing is now also placed in the context of Industry 4.0, which is the integration of digitalization, automation, and intelligent systems in manufacturing (Ghobakhloo, 2020). Three interrelated technological areas are at the centre of this transition. First, digital infrastructure, such as 5G, artificial intelligence (AI) and the industrial internet, serves as a platform for the green transformation of cities, nations and transnational regions (Deng & Zhong, 2024), where the central pillars of low-carbon manufacturing are cyber-physical systems and the Industrial Internet of Things (IIoT) (Bai et al., 2020; Ghobakhloo, 2020). Second, industrial robotics has seen a rapid growth as around 3.9 million industrial robots are currently deployed in factories across the world, and robots are now being discussed as tools for environmental governance, but also productivity (IFR, 2023). Thirdly, hybrid manufacturing, which integrates additive manufacturing and subtractive manufacturing, is a potentially beneficial method to reduce waste, energy consumption and carbon footprint (Liu et al., 2024), and life cycle analysis has shown a significant reduction in CO₂ emissions compared to traditional machining processes (Kokare et al., 2023; Peng et al., 2018; Ford & Despeisse, 2016).

While there is significant literature on each of these technologies separately, there are no studies that have looked at all three in one place, in one story of technology-enabled decarbonisation. This review addresses that gap in three ways. It (1) brings together the evidence from the three domains of carbon reduction potential of the technologies; (2) highlights three mechanisms that are common across all three

domains (improved energy efficiency, environment-oriented technological innovation, more efficient resource allocation) and (3) identifies the integrated deployment of the three technologies as a specific and largely under-researched research frontier. This comparative claim about the three different literatures is not the same as a study of the effects of combining the technologies, which is not the subject of any of the studies reviewed in this study.

The following questions are used to provide direction for the review:

- RQ1. How can digital infrastructure, industrial robotics and additive–subtractive hybrid manufacturing help to lower carbon emissions in industry and urban areas?
- RQ2. What regional development, governance, industry characteristics and energy rebound effect influence the size and persistence of such effects?
- RQ3. What are the key evidence gaps and, in particular, what has research been done on the combined use of these three technologies for decarbonisation?

The review includes nine focal studies (three in each domain) that were reviewed closely and a larger number of peer-reviewed studies. The review approach is outlined next. The review and critical appraisal of the evidence follows, where the findings of each study are placed within the context of the technology domain, and assessed for its contribution. Finally, cross domain observations are discussed, along with implications for policy, industry and future research, before the paper concludes.

REVIEW APPROACH

This systematic review aims to present the state of the art of peer-reviewed literature on the carbon footprint reduction methods of industry and cities by means of digital infrastructure, industrial robotics and hybrid additive–subtractive manufacturing. It highlights the mechanisms of reduction: energy efficiency, green innovation, factor allocation and material optimization, the value-chain effects, as well as the methodologies of the underlying studies, the impact of regional and contextual aspects, and the key research gaps.

The review is divided into three technology fields: digital infrastructure and digitalization, industrial robots and intelligent automation, and additive–subtractive manufacturing. The content is based primarily on studies published between 2020–2025, with some foundational studies incorporated as relevant. The empirical evidence is mainly from China; evidence from other parts of the world is included to provide a broad perspective. The corpus includes econometric, carbon-modelling and case-study designs and only peer-reviewed articles from Scopus and Web of Science. The review is based on 30 verified sources, nine detailed (three for each domain) and 21 supporting and corroborating sources.

Scopus and Web of Science – the most important databases for indexed academic journals (Mongeon & Paul-Hus, 2016) – were used to conduct a structured search. Although a methodological source, it is considered a part of the 30 verified sources as it directly addresses the rationale for database selection for this review. The search terms included combinations of technology (digital infrastructure, industrial

robots, additive manufacturing, hybrid manufacturing) and sustainability (carbon emissions, carbon footprint, green innovation, energy efficiency, decarbonisation) keywords. Only English language peer-reviewed journal articles, review papers, and systematic reviews were included in the search.

About 1110 records were found in the initial search within the three domains. Following the removal of duplicates and screening of titles and abstracts, 178 remained for full-text review; after reviewing the full texts of these papers, 9 focal studies, providing methodological transparency and empirical validation, and 21 supporting studies were identified and considered. Focal studies were selected as varying analytical levels or approaches in each domain, such as city-, enterprise-, and market-integration analyses of digital infrastructure; globalization and urban analyses of robotics; and life-cycle and integrated carbon-accounting models of hybrid manufacturing. The results of the search and selection are summarised in Table 1.

Table 1: Search and selection of studies

Domain	Database(s)	Initial results	After screening	Focal studies
Digital infrastructure	Scopus + WoS	340	45	3
Industrial robotics	Scopus + WoS	490	60	3
Additive–subtractive manufacturing	Scopus + WoS	280	38	3
Supporting domains)	(all Scopus + WoS	35	35	21 (supporting)
Total	—	1,110	178	30 (9 focal + 21 supporting)

The focal and supporting studies collectively illustrate the interdisciplinary nature of research on decarbonization with technologies. In most studies of digital infrastructures and robotics, panel-data econometrics is applied such as fixed-effects models, spatial econometrics and two-stage least squares (2SLS), whereas the hybrid manufacturing studies are primarily based on carbon-emission modelling and life-cycle assessment (LCA). Case-study designs are used in some studies to focus on the organizational adoption and mediating mechanisms like green technological innovation. The quality of the studies was judged on the basis of methodological transparency, empirical validation, and publication in reputable indexed journals. Preference was given to those studies that clearly mentioned their data sources, model

specifications, robustness checks, and validation procedures. Each of the nine focal studies fulfilled these criteria.

There are two drawbacks to this strategy. Firstly, only English language articles that have been indexed in the Scopus and Web of Science (WoS) databases were searched, which may have excluded grey literature and non-English articles that were pertinent to the topic. Second, because this is a narrative review and not a comprehensive review of the literature, the choice of focal studies and the preponderance of studies based in China means that the evidence presented may not be applicable to other manufacturing economies.

REVIEW AND CRITICAL APPRAISAL

This section summarizes the evidence on a technology-by-technology basis. The principal findings and an assessment of their contribution of the focal studies is given for each domain followed by corroborating evidence and a short synthesis of the domain. Table 2 provides an overview of the nine focal studies, prior to the detailed discussion. Throughout, two interpretive cautions are in effect. First, most of the evidence on digital infrastructure and robotics is observational; while some of these studies attempt to improve the identification of causal effects through fixed-effects, instrumental-variable, or two-stage least-squares approaches, the results should be interpreted as strong correlations rather than causal effects, per se. Secondly, the hybrid-manufacturing evidence is based in process-level energy and material modelling, meaning that the figures refer to modelled physical savings and not to statistically estimated savings.

Table 2: Overview of the nine focal studies

Study	Domain	Method	Scope	Key finding(s)
Deng & Zhong (2024)	Digital infrastructure	Spatial econometrics	284 Chinese cities	Lowers urban emissions via energy conservation, GTI, and factor allocation; positive spatial spillover to neighbouring cities; stronger in eastern/northern, large, non-resource cities
Deng, Cai & Ma (2024)	Digital infrastructure	Panel fixed effects	Listed Chinese manufacturers	Firm-level digital transformation associated with lower carbon-emission intensity via energy efficiency, resource allocation, and GTI

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Wang, Yu & Sun (2024)	Digital infrastructure	DEA measure + two-way FE + 2SLS	Chinese manufacturing (provincial)	Internet development raises carbon-emission efficiency (CEEM) via collaborative governance, industrial upgrading, and green tech; market integration a key channel
Han, Wu, Zhu & Diao (2024)	Robotics	Panel econometrics	Chinese provinces	Robots yield synergistic pollution and carbon reduction; regional pattern “central > west > east”
Zhang, Zhu & Wang (2025)	Robotics	Panel fixed effects (global dataset)	Global manufacturing (countries × industries)	Robots significantly reduce emissions via TFP, cleaner energy mix, and GVC climbing; short-run negative, long-run positive but non-significant (rebound)
Zhang, Wang & Li (2025)	Robotics	Urban panel (TC / PC / CI)	Chinese cities	Robots reduce urban emissions across total, per-capita, and intensity measures; linked to SDG 9, 11, 13, and 7
Panagiotopoulou et al. (2025)	Additive–subtractive	Carbon-accounting / LCA framework	Hybrid (DED + milling) case	Three-level, two-source carbon-accounting framework; DED laser is the highest-emitting subsystem
Top et al. (2023)	Additive–subtractive	Case study	Manufacturing firm	AM as an Industry 4.0 enabler; contributions across design, production, and end-of-life; cross-industry flexibility
Liu et al. (2024)	Additive–subtractive	Integrated carbon-emission model	ASIHM process	~80% lower footprint vs conventional milling; >54% of emissions from additive forming; AM favourable when recycled >60% of volume; model >97% accuracy

Digital Infrastructure and Carbon Reduction

Digital infrastructure is the technological platform to deploy 5G networks, AI, and the industrial internet (Deng & Zhong, 2024). Much evidence supports its association with reductions in urban and industrial carbon emissions, which proceeds in a variety of interactive ways, and which is best documented at the city level.

The city-level analyses in this literature are among the more comprehensive of Deng and Zhong (2024), which use spatial-econometric methods and 284 cities in China. They distinguish three avenues for carbon reduction: energy saving, green technological innovation (GTI), and better factor allocation efficiency, and demonstrate that digital infrastructure enables companies to monitor and adjust their production in real time, leading to precise input–output management while reducing waste of production factors. Their most important findings are a spatial spillover effect: the investment in digital infrastructure in one city is related to the adoption of low-carbon policies in neighbouring cities, and self-reinforcing feedbacks towards sustainable development. The impact is also uneven. Environmental benefits are greater in eastern and northern cities and are greater in large, non-resource cities, and small cities with limited technology infrastructure, resources, and personnel are less able to use digital infrastructure for emissions reduction, indicating the potential for a growing “digital divide” in green-transition capability. The study's primary strengths are that it accounts for heterogeneity and that it is spatially economic, capturing inter-city spillovers which most studies of the digital economy or carbon studies do not.

Deng, Cai and Ma (2024) move from the cities to the enterprise level and demonstrate how firm level digital transformation can increase manufacturing energy efficiency through a change in production and operation, an optimization of resource use and through the promotion of GTI. Companies employ sensors and smart meters to collect data on energy production and consumption and utilize AI and big data technologies to optimize energy production, and empirically, digital transformation is linked to a reduction of the carbon-emission intensity (CEI). The enterprise level is added to the picture at the city- and national-level, and the study provides a micro-foundation to the macro effects noted elsewhere.

Wang, Yu, and Sun (2024) adopt a market-integration perspective and ask the question of whether the development of the Internet enhances the carbon-emission efficiency of manufacturing (CEEM). To tackle endogeneity, they build a carbon-emission-efficiency measure based on data envelopment analysis (DEA) and estimate the determinants of their measure using two-way fixed-effects and two-stage least-squares (2SLS) models. They discover that the internet allows long-range real time data transfer which enhances information availability across regions and that there are three channels—deeper collaborative governance, industrial-structure upgrading, and green-technology advancement—through which it lowers emissions. In particular, the internet strengthens the emissions reducing impact of environmental regulation. The CEEM measure is a comparatively strong measure of the environmental performance of firms, given that it reflects efficiency, and not just the amount of emissions.

Collectively, digital-infrastructure evidence paints a picture of how digital technologies contribute to carbon emissions reductions by enhancing efficiency, innovation, and allocation, with a significant moderation by regional development, governance, and industry structure (Deng & Zhong, 2024).

Industrial Robotics and Carbon Reduction

The use of industrial robots has been increasing at a fast pace. In 2022, the worldwide operational stock of industrial robots totaled approximately 3.9 million units, increasing by 12% compared to the previous year, and annual installations reached a record high of 553,052 units (IFR, 2023). In addition to productivity, robots are also being used as tools of environmental governance and there is an emerging literature that documents a link between robot adoption and carbon reduction (Guo et al., 2024; Lin & Xu, 2024; Acemoglu & Restrepo, 2020).

Han et al. (2024) explore the synergy between pollution reduction and carbon-emission reduction from robot use (Synergy of Pollution Reduction and Carbon-emission reduction from robot use (SEPRCE)). The sensing technologies of the robots can identify pollution indicators and collect environmental information, effectively treat the pollutant and adjust the treatment method. The study's original contribution is that the regional pattern, that is, the “central > west > east” effect, is largely related to the different initial technological endowment, energy structure and the maturity of the innovation-ecosystems across China, thereby indicating the different impact of robots on the environment. This corroborates the results of Lin and Xu (2024) finding that robots decrease firm energy intensity via technological innovation and electrification, and Li and Zhou (2024) finding positive effects of robots on TFP in urban areas.

The most methodologically ambitious of the focal studies of robotics is by Zhang, Zhu, and Wang (2025) and is based on a global data set; they test several different hypotheses: a productivity effect, global-value-chain (GVC) climbing, and energy-rebound dynamics. They discover that in global manufacturing, the widespread adoption of industrial robots is tightly and negatively related to carbon emissions, in part by means of a “climbing effect”, which means an increase in a country's standing in the division of labour of the GVC. These mechanisms are extensions of the economic framework established by Acemoglu and Restrepo (2020), and include both higher TFP and a smaller share of fossil fuels and lower energy intensity. The openness in the discussion of the energy-rebound effect and of the limits of technology transfer to developing countries is a welcome sign, lending credibility to the study's conclusions and providing an important caution for research and policy. The authors report a negative, statistically significant effect of robots on emissions in the short run, and a positive but statistically insignificant effect in the long run, specifically in the case of rebound. With the continuous advancement of digital technologies and the continuous expansion of information infrastructure, the application of digital technologies in intelligent manufacturing is still expanding, and energy consumption in 5G base stations and data centres is increasing rapidly. The rebound effect in all of the evidence examined diminishes, but does not eliminate, the carbon benefit from the use of robots.

Zhang, Wang and Li (2025) add an urban-level analysis based on three indicators (total carbon emissions, TC; per capita carbon emissions, PC; and carbon intensity, CI) and draw a direct link between the use of robots and the Sustainable Development Goals (SDG 9: Industry, innovation and infrastructure; SDG 11: Sustainable cities and communities; and SDG 13: Climate action, and, additionally, SDG 7: Affordable and clean energy through the optimization of renewable-energy systems). The explicit SDG linkage provides the study with a normative element that links technological advances to global sustainability

goals, and the urban focus connects firm-level and macro-level research. Based on this, the authors recommend zones for automation and international cooperation in the field of robotics for urban decarbonisation. The rebound caution is confirmed by Jin (2024), who identifies the energy demand of wide-spread deployment of robotic and digital technologies as a policy issue.

Crossing national boundaries, Chen et al. (2025) include a trade-network dimension, positing that industrial robots are complex green goods that internationalise the transfer of technological knowledge when adopted and provide environmental benefits across the network. On this view, the carbon-saving effects of robot adoption are not contained within the borders of the country that adopted the robots, but, instead, spread across countries, as proposed by Acemoglu and Restrepo (2020) in their theory of technology spillover.

Overall, the robotics evidence suggests that there are productivity, cleaner energy mix and value chain upgrading gains in terms of carbon emissions reduction, although there is a significant regional variation and a partial energy rebound effect that reduces, but does not negate, the benefit.

Additive–Subtractive Hybrid Manufacturing and Carbon Reduction

Hybrid manufacturing (HM) is a growing research field that integrates additive (AM) and subtractive (SM) manufacturing methods and is being used to promote sustainable manufacturing. AM techniques like directed energy deposition (DED), powder Bed Fusion (PBF), and Wire Arc Additive Manufacturing (WAAM) can help to reduce energy and material consumption by minimizing waste generation, since they do not require removal of unnecessary material, and idle time (Panagiotopoulou et al., 2025). Life-cycle assessments show that AM can save CO₂ emissions not only due to lighter parts, but also by reducing material waste and optimizing part design: Primary energy savings of 2.54–9.30 EJ and CO₂ emissions savings of 130.5–525.5 Mt of CO₂ were estimated for additively manufactured products by 2025 (Gebler et al., 2014).

The most detailed approach to carbon accounting from the key studies is that of Panagiotopoulou et al. (2025), who distinguish between analysis at the three levels of process, machine tool, and system, and two emission sources (energy and material). From the process perspective, the laser machine is one of the most energy-consuming subsystems in the machine, and the fact that the laser machine is the largest emitter is a help in identifying a target for the intervention to be taken. This process-level view aligns with the overall result that the energy consumption per kg of deposited material can vary orders of magnitude among the various AM process families, and thus that route selection can materially affect the carbon outcome (Colorado et al., 2020).

AM can be seen as a key enabler in the transition from conventional manufacturing to Industry 4.0, as discussed by Top et al. (2023) who argue it has revolutionized the manufacturing process. AM's unique feature, which is the ability to create customized products at a low cost, can be seen in its applications in the defence industry, aerospace, architecture, automotive industry, healthcare, and textiles, and the AM contribution to sustainability has been reported at the design, production, and end-of-life stages of the product life cycle (Niaki et al., 2019). While this cross-industry overview is more conceptual than the

other focal studies, it serves as a useful framing for the flexibility of AM in the dual digital and sustainable transition (Chen et al., 2023).

Liu et al. (2024) provide the most detailed quantitative assessment among the focal studies. They verify an integrated model of the carbon emissions of additive–subtractive integrated hybrid manufacturing (ASIHM), a type of HM that integrates additive and subtractive manufacturing on a single machine platform, achieving a prediction accuracy of more than 97%. The model shows that with ASIHM, the carbon footprint can be reduced by about 80% compared to traditional milling. The emissions are generated on three occasions: during additive manufacturing using the laser, during milling of the additive manufacturing residual parts and during the switching of the additive laser head and subtractive tool, with the greatest part of the emissions occurring during the additive manufacturing stage (more than 54%). AM is also more environmentally friendly than traditional production methods when more than 60% of the volume of the newly created part is made from recycled materials. The results are in accordance with the circular economy thresholds of metal AM reported by Colorado et al. (2020) and Peng et al. (2018).

Overall, the evidence on hybrid-manufacturing suggests significant carbon savings from both additive and additive–subtractive manufacturing compared to subtractive-only manufacturing, which occur during the additive forming stage, and are dependent on a high content of recycled material.

DISCUSSION AND IMPLICATIONS

Cross-Domain Observations

The three literatures are similar in structure if they are read side by side. In all three domains, the three mechanisms that lead to carbon reductions are the same: energy efficiency, technology innovation with environmental focus and more efficient allocation of resources/factors. Digital infrastructure and real-time monitoring and optimization enable them, while robotics through productivity gains, electrification, and value-chain upgrading, and hybrid manufacturing through material efficiency and reduced machining. This convergence is observed in three distinct bodies of evidence, and none of the studies analyzed in this review investigates the combination of digital infrastructure, robotics and hybrid manufacturing (RQ3). It is also unclear whether the mechanisms reinforce each other, e.g. whether the energy demanded by the data-centre and by the base-station that supports digital and robotic systems, outweighs the energy saved during the manufacturing process, or vice versa, as explored in the section on scope for future research below.

Policy Implications

This review provides several policy implications for governments undertaking low-carbon industrial transitions. Digital infrastructure, industrial robots and advanced manufacturing should be considered strategic assets in climate policy with differentiated implementation depending of the regional conditions.

The spatial spillover effect (investment in one city is associated with lower emissions in others, as in Deng & Zhong, 2024) suggests regional-coordination mechanisms and shared digital platforms, enabling

the sharing of experience; support will be needed for small cities with limited technical capacity, to avoid a ‘digital divide’ in green-transition capacity.

Advanced economies should promote the development of highly accurate, low-energy robots (Zhang, Zhu & Wang, 2025) and developing economies should plan the use of robots according to emission reduction policies; energy efficiency labels can be used together with robotics, and energy-rebound effect should be addressed in the policies (Zhang, Zhu & Wang, 2025; Wang et. al., 2023; Chen et al., 2025).

Governments and industry should encourage hybrid additive–subtractive manufacturing in the context of green-manufacturing strategies, particularly in aerospace, automotive and medical industries. CO₂ savings from investment incentives and R&D on the laser efficiency and optimization of the switching process — the key emission sources identified for ASIHM — can be significant, and Liu et al.'s (2024) 60%-recycled-material threshold provides a reasonable benchmarking target.

Industry and Practice Implications

For manufacturers, there are several implications related to the importance of digitalization both economically and environmentally. Sensors, AI-based monitoring and the industrial internet can optimize production in real-time, which can save energy and reduce emissions (Deng, Cai & Ma, 2024). The carbon savings in automotive and heavy-equipment production (Zhang, Zhu & Wang, 2025; Han et al., 2024; Shah et al., 2023) indicate that the impact of robot use will be most significant in capital-intensive industries. The large carbon advantage of additive–subtractive manufacturing over traditional milling makes it an excellent candidate for investing in hybrid-manufacturing systems, especially when dealing with low-volume or complex-geometry manufacturing; as the additive forming stage is the main source of these emissions, the focus of investment in laser efficiency and renewable energy supply should be enhanced in this stage.

Scope for Future Research

There are four main areas for future research. First, this triple deployment of digital infrastructure, intelligent robotics and hybrid manufacturing is largely under-researched at present. The main gap identified in this review is the study of synergistic emissions effects of integration of the three, which include whether their mechanisms reinforce or offset each other, and would guide the design of next generation sustainable manufacturing systems consistent with Industry 5.0 and smart-manufacturing paradigms (Ghobakhloo, 2020).

Second, the empirical base is very much concentrated in China; cross-national research is required for external validity. Third, the long run dynamics of carbon reduction with technology needs longitudinal research (the energy rebound robot effect is found to be statistically non-significant, Zhang, Zhu & Wang (2025)). Fourth, the relationship between these technologies and the SDGs (especially SDG 7, SDG 9, SDG 11, SDG 13) could be examined by future research.

CONCLUSION

Drawing on nine focal studies, complemented by 21 peer-reviewed sources, this study has examined the role of digital infrastructure, industrial robotics, and hybrid additive–subtractive manufacturing in industry and cities in relation to their potential to reduce carbon emissions. In all three domains, the evidence suggests that three mechanisms of decarbonization are recurrent: energy efficiency, technological innovation with an environmental focus, and more efficient use of resources.

These effects are neither automatic nor universal. The relationships vary by factors such as regional heterogeneity, industry structure, stage of development, and the energy rebound effect and the difference in adoption capacity between developed and developing economies. A supportive policy and institutional framework are thus as important as the technologies for realizing their carbon benefit.

The integrated potential of this convergence of digital infrastructure, intelligent robotics, and advanced manufacturing, as shown in this review, offers a compelling, evidence-based technological path forward, especially as the global commitments to reach net zero under the Paris Agreement, SDGs and national carbon-neutrality pledges grow.

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