frontiers | Frontiers in Energy Research

TYPE Review
PUBLISHED 25 June 2025
DOI 10.3389/fenrg.2025.1460586

OPEN ACCESS

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RECEIVED 06 July 2024
ACCEPTED 02 January 2025
PUBLISHED 25 June 2025

CITATION
Mhlanga D (2025) AI beyond efficiency, navigating the rebound effect in AI-driven sustainable development.
Front. Energy Res. 13:1460586.
doi: 10.3389/fenrg.2025.1460586

AI beyond efficiency, navigating the rebound effect in AI-driven sustainable development

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Integrating Artificial Intelligence (AI) across industries has significantly enhanced operational effectiveness, positioning AI as a critical driver of sustainable development. However, this relationship is complex due to the rebound effect, where efficiency improvements paradoxically increase overall resource consumption. This study employs a systematic literature review of 150 articles published in the last decade, with 41 analyzed in detail, focusing on AI applications in transportation, energy, and manufacturing. The findings reveal that while AI-driven advancements reduce energy use per unit, they often lead to higher overall consumption, potentially negating environmental benefits and hindering progress toward sustainability objectives. This research explores the dualistic impact of AI on sustainable development and provides a comprehensive analysis of its influence on energy consumption patterns and broader implications for sustainability goals. To address these challenges, the study proposes a comprehensive strategy combining technological innovation, legislative measures, and behavioural interventions to mitigate the rebound effect and maximize AI's potential for long-term sustainability. This work contributes to the ongoing dialogue on sustainable development by highlighting the importance of a balanced approach that addresses AI's benefits and challenges in achieving sustainability objectives.

KEYWORDS

artificial intelligence, beyond efficiency, rebound effect, sustainable development, sustainability

Introduction

In the era of rapid technological advancement, Artificial Intelligence (AI) stands out as a pivotal force shaping the future of global industries and environmental strategies. AI technologies are positioned at the forefront of the quest for sustainable development by optimising processes and enhancing operational efficiencies. Sustainable development aims to balance the fulfilment of human needs with the protection of the natural environment, ensuring these needs can be met by the present and future generations (United Nations, 2023). Consequently, improving energy efficiency is crucial for sustainable development as it helps reduce the overall consumption of finite resources and decrease environmental pollution. AI significantly enhances energy efficiency across various sectors by optimizing energy use, reducing waste, and enabling more competent resource management (IEA, 2022; Mhlanga, 2023a). For instance, AI-driven technologies in transportation, manufacturing, and energy production sectors have shown considerable promise in lowering energy consumption and emissions (Zhou et al., 2023). Artificial Intelligence (AI) has emerged as a critical tool for optimizing resource use, potentially significantly improving energy efficiency across various sectors. Rather than directly enhancing energy efficiency, AI-driven algorithms enable smarter resource management, optimizing energy use, reducing waste, and improving operational efficiencies (IEA, 2022). However, while AI can make activities like driving, heating, and high-data computing more efficient, this increased efficiency often leads to expanded usage, a phenomenon known as the rebound effect (Sorrell, 2009). This paradoxical outcome can negate the initial environmental benefits of AI adoption (Brockway et al., 2021).

In Fact, despite the promising synergy between AI and energy efficiency, this relationship is complicated by the rebound effect a phenomenon where increases in efficiency lead to a paradoxical increase in overall resource consumption. Originally identified by William Stanley Jevons about coal use in the 19th century, the rebound effect remains a significant challenge in modern environmental economics and policymaking (Jevons, 1865; Greening et al., 2000). As AI technologies make energy use in activities such as driving, heating, and high-data computing more efficient, the lower costs and increased capabilities can lead to expanded usage, potentially negating the environmental benefits (Sorrell, 2009; Mhlanga 2023b). This paradox underscores the complexity of achieving sustainable development goals in the age of AI. Moreover, the dualistic impact of AI on sustainable development through the lens of the rebound effect presents a core challenge. While AI can significantly enhance the efficiency of systems and reduce per-unit energy consumption, these improvements often encourage greater overall consumption. This increased consumption occurs either by lowering costs or enhancing service attractiveness, thus exacerbating environmental impacts rather than mitigating them (Brockway et al., 2021; Mhlanga 2023c). Hence, understanding this dual impact is essential for policymakers and stakeholders aiming to leverage AI for sustainable development.

This paper seeks to dissect the complexities of this relationship, exploring how AI-driven efficiencies in various sectors might inadvertently lead to higher overall energy usage and environmental degradation. The purpose is to critically analyse how AI influences energy consumption patterns through the rebound effect and assess this phenomenon's implications for sustainable development goals (Madlener and Turner, 2016). We aim to explore both the challenges and opportunities AI presents in achieving sustainable outcomes, focusing on sectors where AI's impact is most pronounced. Furthermore, this exploration will provide strategic insights into policy measures, technological innovations, and behavioural changes needed to mitigate the rebound effect. Through a comprehensive review of current practices and potential solutions, this paper will contribute to a more nuanced understanding of how to harness AI's capabilities for sustainable development (Gillingham et al., 2013). Furthermore, this paper explores how AI's dualistic impact on sustainable development, particularly in transportation, energy, and manufacturing, can complicate achieving long-term sustainability goals. This exploration will provide strategic insights into mitigation policies, such as implementing regulatory frameworks and promoting behavioural interventions, to maximize the benefits of AI while minimizing adverse outcomes. In summary, by addressing the dualistic impact of AI on energy efficiency and consumption, this paper aims to offer a balanced perspective on the potential of AI technologies. The findings and recommendations will be valuable for policymakers, industry leaders, and researchers working towards integrating AI into sustainable development frameworks. Ultimately, the problem statement guiding this chapter is: How can the benefits of AI-driven energy efficiency be maximized while minimizing the adverse effects of the rebound effect on sustainable development?

Systematic literature review methodology

Review questions

The systematic literature review will address the following specific questions:

RQ1-What are the primary ways AI is employed to enhance energy efficiency across various sectors?

RQ2-What evidence demonstrates the rebound effect in AI-driven initiatives aimed at sustainability?

RQ3-What mitigation strategies are identified or proposed to counteract the rebound effect in applying AI technologies?

The systematic literature review will address the following questions: What are the primary ways AI is employed to enhance energy efficiency across various sectors? What evidence demonstrates the rebound effect in AI-driven initiatives aimed at sustainability? What mitigation strategies are identified or proposed to counteract the rebound effect in applying AI technologies?

The inclusion criteria for the reviewed articles included studies published within the last decade (2013–2023), focusing on AI's role in energy efficiency and the rebound effect. Peer-reviewed journal articles and conference proceedings were prioritized, while grey literature and non-peer-reviewed sources were excluded. Studies were assessed for their direct relevance to the research questions outlined in this study.

The systematic literature review (SLR) conducted for this paper reviewed 150 articles published in the last 10 years, focusing on the use of AI to enhance energy efficiency and the presence of the rebound effect. After a rigorous screening process, 30 studies were selected for detailed analysis, examining AI's impact in the transportation, energy, and manufacturing sectors. This SLR differs from previous reviews by providing an in-depth sector-specific focus on the rebound effect in AI applications and offering actionable mitigation strategies. To ensure a comprehensive approach to the research methodology, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodological flowchart is illustrated in Figure 1.

Articles that focus on the application of AI in improving energy efficiency and examining the rebound effect were included in the review. Peer-reviewed journal articles and conference proceedings were the source of quality articles included in the review. Grey literature, opinion pieces, and non-peer-reviewed reports were excluded. The systematic literature search was conducted in databases such as IEEE Xplore, PubMed, Scopus, and Web of Science. Keywords including 'artificial intelligence,' 'sustainability,' 'energy efficiency,' and 'rebound effect' were used in various combinations to retrieve relevant articles. The search followed the PRISMA methodology, ensuring a rigorous and transparent process.

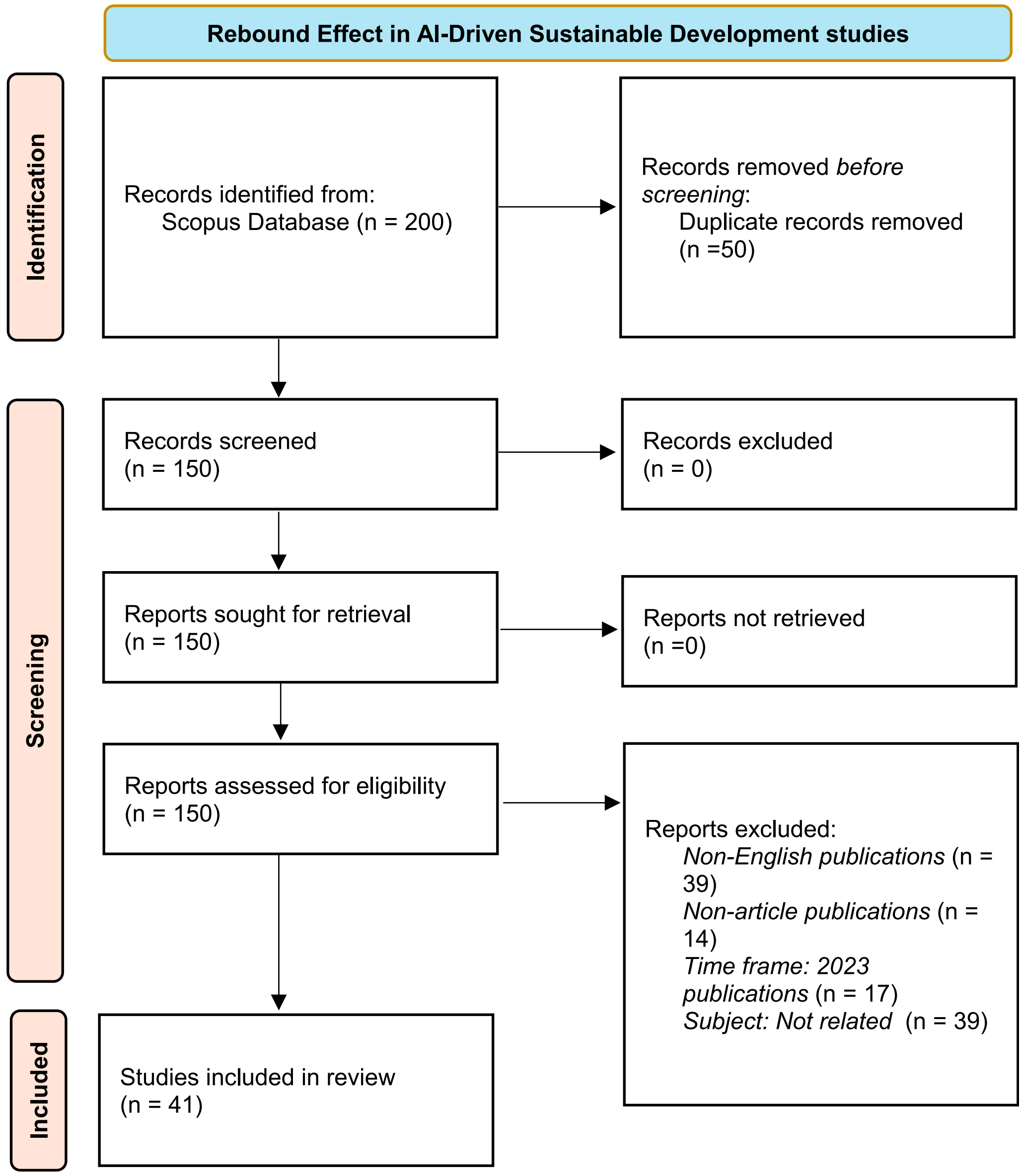

FIGURE 1
PRISMA Methodological flowchart.

The selection process involved screening, where titles and abstracts were reviewed to filter out irrelevant papers; eligibility assessment, where full-text articles will be assessed to ensure they meet all inclusion criteria; and inclusion, which involves the final selection of studies for detailed review. Data will be extracted on study design and methodology, specific AI technologies discussed, impact on energy efficiency, evidence of the rebound effect, and proposed or evaluated mitigation strategies. The quality of included studies was evaluated using the CASP checklists, ensuring that only high-quality, relevant research informs the review conclusions. Data was synthesized using qualitative analysis through thematic analysis for narrative data and quantitative analysis through meta-analysis techniques if applicable to aggregate findings and derive statistical significance. The findings were compiled following the PRISMA guidelines, ensuring a systematic and transparent reporting of the review process. The review was prepared for publication in a scientific journal and presented at relevant conferences. Given the fast-paced advancements in AI, an update of this review will be planned every 2 years to incorporate the latest research findings. This systematic review provided comprehensive insights into how AI technologies influence energy efficiency and the extent of the rebound effect in sustainable development initiatives. The review offered valuable information for developing strategies to mitigate negative outcomes and harness AI's potential responsibly.

AI and energy efficiency

Artificial Intelligence (AI) has become a cornerstone technology in driving energy efficiency across multiple sectors. By leveraging data analysis, predictive modelling, and automated control systems, AI enhances operational efficiencies and paves the way for significant reductions in energy consumption. This section explores the impact of AI in three key sectors: transportation, data centres, and manufacturing, highlighting specific case studies where AI has enabled notable energy efficiency improvements.

Transportation

In the transportation sector, AI technologies have revolutionized how vehicles are operated and managed. Autonomous vehicles, for instance, utilize AI to optimize routes and improve fuel efficiency. A notable example is the use of AI by shipping and logistics companies to minimize fuel consumption. UPS, a global logistics leader, implemented its On-Road Integrated Optimization and Navigation (ORION) system, which uses AI to determine the most efficient delivery routes. This system analyzes daily delivery routes and the ever-changing road conditions to minimize left turns and reduce idling time. Since its full deployment, ORION has reportedly saved over 10 million gallons of fuel and reduced emissions substantially by decreasing the miles driven by delivery trucks. Additionally, AI applications in public transportation systems have shown significant potential in improving efficiency and reducing energy consumption. For instance, Transport for London (TfL) employs AI to manage and predict bus and train schedules, ensuring that public transport runs on time and minimizes energy wastage. AI algorithms analyze vast amounts of data, including traffic conditions, passenger numbers, and historical travel patterns, to optimize schedules and routes, reducing fuel consumption and lowering emissions. Another example is the use of AI in ride-sharing services like Uber and Lyft. These companies leverage AI to match passengers with drivers efficiently, optimize ride routes, and reduce wait times. By using machine learning algorithms, these platforms can predict demand in real-time, allowing for better allocation of resources and minimizing unnecessary driving. This optimization improves the user experience and reduces the total number of vehicle miles travelled, thereby decreasing fuel consumption and emissions.

In the aviation industry, AI enhances fuel efficiency through better flight planning and maintenance scheduling. Airlines use AI to analyze weather patterns, air traffic data, and aircraft performance to optimize flight paths and reduce fuel burn. For example, Southwest Airlines has implemented an AI-based system for predictive maintenance, which anticipates potential mechanical issues before they occur, reducing unplanned downtime and improving overall operational efficiency. Similarly, AI-driven flight planning tools help pilots choose the most fuel-efficient routes, considering factors like wind speed and direction, which can lead to substantial fuel savings over time. These examples demonstrate the transformative impact of AI on the transportation sector, showcasing how AI technologies can significantly improve fuel efficiency and reduce emissions. However, it is important to note that while AI-driven efficiencies contribute to environmental benefits, they also present the risk of the rebound effect. As operational costs decrease due to increased efficiency, there may be a tendency for increased usage, which could potentially offset the gains made. Therefore, it is crucial to implement complementary measures, such as regulatory policies and behavioural interventions, to ensure that the environmental benefits of AI technologies are fully realized without unintended negative consequences.

Data centres

Data centres, known for their high energy consumption, have benefited significantly from AI applications. Google's use of DeepMind AI to optimize the cooling systems in its data centres serves as a profound case study. By analysing sensor data and adjusting cooling systems in real-time, the AI system has reduced cooling energy usage by up to 40%, showcasing a groundbreaking application of machine learning for energy management. This illustrates direct energy savings and enhances the overall Power Usage Effectiveness (PUE) of the facilities, making them more efficient and sustainable. In addition to Google's innovative approach, other tech giants have also adopted AI to improve the energy efficiency of their data centres. For instance, Microsoft employs AI to manage its data centre operations, leveraging machine learning to predict server loads and optimize energy consumption. By analyzing historical data and real-time inputs, Microsoft's AI systems can dynamically adjust cooling and power usage, significantly reducing the energy required to keep servers at optimal operating temperatures. This proactive management approach has enabled Microsoft to achieve substantial energy savings and lower its carbon footprint. Similarly, Facebook utilizes AI to optimize the performance of its data centres. The company has developed an AI-driven thermal management system that monitors and adjusts the cooling mechanisms to maintain optimal temperatures while minimizing energy use. This system uses a combination of predictive analytics and real-time data to fine-tune cooling processes, resulting in significant energy reductions and improved operational efficiency. By continually learning from the data collected, Facebook's AI system can make increasingly precise adjustments, further enhancing energy efficiency over time.

AI's impact on data centre energy efficiency extends beyond cooling systems. AI algorithms are also used to optimize server workloads and improve resource allocation. For example, AI can predict which servers are likely to experience high loads and distribute tasks, accordingly, ensuring that resources are used efficiently and reducing the need for excess capacity. This intelligent load balancing enhances performance and minimizes energy wastage, contributing to overall energy savings. Furthermore, AI can help data centres transition to renewable energy sources by optimizing the integration of solar and wind power into their operations. AI systems can predict energy production from renewable sources based on weather forecasts and historical data, allowing data centres to plan their energy usage more effectively and reduce reliance on non-renewable energy. This approach not only supports sustainability goals but also helps in managing energy costs. These examples highlight the transformative potential of AI in enhancing the energy efficiency of data centres. However, it is important to consider the potential rebound effect. As data centres become more energy-efficient and operational costs decrease, there may be a tendency to increase the scale and scope of data center centres become more energy-efficient and operational costs decrease; there may be a tendency to increase the scale and scope of data centre operations, potentially offsetting the energy savings achieved. To mitigate this risk, it is essential to implement policies and practices that promote sustainable growth and encourage the use of renewable energy sources. AI technologies have made significant strides in improving the energy efficiency of data centres, leading to substantial reductions in energy usage and enhanced operational performance. By leveraging AI for real-time optimization of cooling systems, workload management, and integration of renewable energy, data centres can achieve greater sustainability. However, careful management is needed to ensure that consumption increased overall consumption does not undermine these gains.

Manufacturing

AI's role in improving energy efficiency is evident in manufacturing through smart manufacturing systems that integrate AI to optimize production processes. Siemens, for example, has deployed AI in its factories to monitor energy usage and predict machine maintenance, which in turn reduces downtime and energy wastage. One factory in Germany employed AI algorithms to analyze operational data, resulting in a 20% reduction in energy consumption without sacrificing output quality or quantity. Beyond Siemens, other manufacturers are also leveraging AI to enhance energy efficiency. General Electric (GE) uses AI-driven predictive analytics to monitor the performance of its machinery and equipment in real time. By detecting potential issues before they lead to failures, GE's AI systems help reduce unplanned downtime and optimize the energy consumption of manufacturing processes. This predictive maintenance approach ensures that machinery operates at peak efficiency, minimizing energy waste and extending the lifespan of equipment. Similarly, in the automotive industry, AI is used to streamline production lines and reduce energy usage. Tesla, for instance, employs AI to monitor and manage its Gigafactories, which produce batteries and electric vehicles. AI systems at these facilities analyze data from numerous sensors to optimize manufacturing processes, from material handling to assembly. This real-time optimization helps Tesla reduce energy consumption, lower production costs, and increase efficiency. In the food and beverage industry, AI is also making significant strides. Nestlé has implemented AI technologies in its manufacturing plants to monitor energy usage and optimize production schedules. Nestlé's AI systems can adjust operations to reduce energy use without compromising product quality by analysing data on energy consumption patterns, production demands, and equipment performance. This approach has led to substantial energy savings and enhanced sustainability in Nestlé's manufacturing processes.

Another example is the use of AI in the textile industry. Companies like H&M and Zara are incorporating AI to optimize their supply chains and production processes. AI algorithms help these companies forecast demand more accurately, reducing overproduction and minimizing waste. Additionally, AI systems optimize the energy consumption of textile manufacturing processes by adjusting machine operations and scheduling maintenance activities based on predictive analytics. This not only improves energy efficiency but also enhances the overall sustainability of textile production. AI's impact on energy efficiency in manufacturing is also seen in the chemical industry. BASF, a global chemical company, uses AI to optimize production processes and reduce energy consumption. By integrating AI into its manufacturing operations, BASF can monitor chemical reactions in real-time and adjust parameters to ensure optimal energy use. This has resulted in significant energy savings and improved environmental performance for the company. These examples demonstrate the significant potential of AI to improve energy efficiency in manufacturing across various industries. However, addressing the potential rebound effect is important, where increased efficiency could lead to higher overall consumption. As manufacturing processes become more efficient and costs decrease, production may tend to increase, potentially offsetting the energy savings achieved. To mitigate this risk, manufacturers should adopt a holistic approach that includes sustainable production practices, regulatory compliance, and continuous energy consumption monitoring. AI technologies are revolutionizing energy efficiency in manufacturing by optimizing production processes, predicting maintenance needs, and reducing downtime. Large corporations like UPS, Tesla, and Google have successfully integrated AI to enhance operational efficiency. For example, UPS's On-Road Integrated Optimization and Navigation (ORION) system utilizes AI to optimize delivery routes, saving over 10 million gallons of fuel annually by minimizing left turns and reducing idling (UPS, 2021). Similarly, Tesla employs AI in its Gigafactories to optimize energy use in manufacturing electric vehicles and batteries, contributing to reduced operational costs and emissions (Tesla, 2022). Google's DeepMind AI reduced energy consumption in data centers by 40% by optimizing cooling systems (Google, 2020). In addition, Companies like Siemens, GE, Nestlé, and BASF are leading the way in leveraging AI to achieve substantial energy savings and enhance sustainability. However, it is crucial to implement strategies to manage the rebound effect and ensure that the environmental benefits of AI-driven efficiencies are fully realized without unintended negative consequences.

Table 1 provides a comprehensive summary of the key findings related to the impact of Artificial Intelligence (AI) on energy efficiency across the transportation, data centers, and manufacturing sectors. It highlights the specific AI applications employed within each sector, the efficiency gains achieved through these technologies, and the rebound effects observed as a consequence of these advancements. Additionally, the table outlines proposed mitigation strategies aimed at addressing the unintended consequences of the rebound effect, supporting sustainable development objectives. This summary serves to synthesize the reviewed literature and offers actionable insights for policymakers, industry leaders, and researchers.

The rebound effect in the context of AI

The rebound effect, a phenomenon where increases in technological efficiency led to higher overall consumption, presents a significant challenge in the application of AI across various industries. This section explores how the efficiencies introduced by AI can inadvertently fuel greater resource use and

TABLE 1 Summary of key findings in AI-driven energy efficiency across sectors.

Sector	AI applications	Efficiency gains	Rebound effect observed	Proposed mitigation strategies
Transportation	- Autonomous driving - Route optimization	- Reduced fuel consumption - Improved traffic flow	- Increased vehicle usage due to lower operational costs - Higher emissions from expanded travel activity	- Implement usage caps - Promote public transportation - Introduce behavioral interventions
Data centers	- AI for cooling optimization - Predictive load balancing	- Reduced energy consumption for cooling - Enhanced resource allocation	- Increased computational demand - Expansion of data services leading to higher energy consumption	- Integrate renewable energy - Use tiered pricing for heavy energy users
Manufacturing	- Predictive maintenance - Smart production systems	- Reduced downtime and waste - Lower energy per unit produced	- Increased production scale due to cost reductions - Greater resource consumption overall	- Promote circular economy practices - Enforce stricter production regulations

examines specific instances of the rebound effect in different sectors. In the automotive industry, AI-enhanced technologies such as autonomous driving and predictive maintenance improve fuel efficiency and vehicle longevity. However, these enhancements can also lead to increased vehicle usage. For example, as autonomous vehicles make travel more convenient and accessible, people might drive more often or for longer distances, potentially increasing total fuel consumption. Additionally, the convenience of autonomous vehicles could increase the number of vehicles on the road, as driving becomes more accessible to different demographics, including the elderly and differently abled individuals. In residential settings, smart thermostats are designed to improve energy efficiency by optimizing heating and cooling cycles based on user behaviour and weather predictions. While these devices can significantly reduce the energy used per heating or cooling event, their convenience and effectiveness might encourage homeowners to maintain more comfortable temperatures year-round rather than adjusting the thermostat manually. This comfort-driven usage could result in higher overall energy consumption despite the efficiencies gained on a per-user basis. While AI enhances operational efficiencies, its potential to increase overall consumption requires a nuanced analysis. For instance, the widespread adoption of autonomous vehicles could increase road usage as more people, including the elderly and differently abled, opt for private vehicles due to enhanced accessibility. However, this increased vehicle usage risks higher emissions and demands mass production of sensors, batteries, and other components. The environmental implications of sourcing raw materials and managing waste from these technologies remain a significant concern (Vivanco, 2022). In addition, the ethical challenges posed by AI, such as data privacy and fairness, require further exploration.

In the context of data centres, AI can optimize operations, reducing energy consumption per computation. However, as data processing becomes more efficient and cost-effective, companies might perform more complex computations or expand their digital services, leading to a surge in the total energy consumed by data centres globally. This effect is particularly evident in sectors like cloud computing and big data analytics, where the demand for AI-driven services grows exponentially. These examples illustrate that while AI can enhance efficiency and reduce the energy consumption of individual processes or products, it also has the potential to increase total consumption through behavioral and economic changes. The rebound effect is also visible in industrial applications. AI-driven predictive maintenance and real-time production adjustments in manufacturing can greatly reduce waste and enhance production efficiency. However, lower production costs can increase production volumes as companies capitalize on cheaper manufacturing processes to boost output and meet growing consumer demand. This scale of production, fueled by reduced unit costs, can ultimately result in greater resource consumption overall.

Even in the agricultural sector, AI applications such as precision farming and automated irrigation systems are designed to optimize resource use and increase crop yields. However, the efficiencies gained might encourage farmers to expand their cultivated areas or intensify production, leading to greater water use, fertilizers, and other inputs. This increased agricultural activity, while efficient on a per-unit basis, can result in higher total resource consumption and environmental impact. Addressing the rebound effect in the context of AI requires a multifaceted approach. Policymakers, businesses, and consumers must know these dynamics to make informed decisions that align with long-term environmental sustainability. Regulatory measures such as setting minimum efficiency standards and implementing usage caps can limit the extent of increased consumption. Consumer education plays a vital role in making individuals aware of the environmental impacts of their choices and encouraging responsible use of AI-enhanced systems. Additionally, advancing AI technologies to focus on individual efficiency and optimizing system-wide resource use can help achieve actual reductions in total consumption. The rebound effect presents a significant challenge to the application of AI across various industries. While AI-driven efficiencies can lead to substantial energy savings and operational improvements, they can also inadvertently fuel greater resource use. Understanding and mitigating this effect is essential to ensure that advances in AI contribute positively to sustainability goals rather than unintentionally exacerbating consumption patterns. The challenge lies in improving technological efficiencies and managing the human behaviours that these technologies alter.

Conceptual overview

AI-driven improvements often lead to decreased costs and enhanced capabilities, which can change user behaviour and market dynamics. For instance, as AI technologies make processes more energy-efficient, the reduced cost of operation might encourage businesses and consumers to use these technologies more frequently or intensively, thus potentially increasing total energy consumption despite the per-unit savings. This phenomenon is critical to understand because it can undermine the environmental benefits expected from technological advancements in AI.

Examples of the rebound effect

Automotive industry

In the automotive sector, AI-enhanced features such as autonomous driving and predictive maintenance improve fuel efficiency and vehicle longevity. However, these enhancements can also lead to increased vehicle usage. For example, as autonomous vehicles make travel more convenient and accessible, people might drive more often or for longer distances, potentially increasing total fuel consumption. Additionally, the convenience of autonomous vehicles could increase the number of vehicles on the road, as driving becomes more accessible to different demographics, including the elderly and the differently abled.

Home heating and cooling

Smart thermostats are another AI application designed to improve energy efficiency in residential settings by optimizing heating and cooling cycles based on user behavior and weather predictions. While these devices can significantly reduce the energy used per heating or cooling event, their convenience and effectiveness might encourage homeowners to maintain more comfortable temperatures year-round, rather than adjusting the thermostat manually. This comfort-driven usage could result in higher overall energy consumption, despite the efficiencies gained per-use.

Data centers

As previously mentioned, AI can optimize data center operations, reducing energy consumption per computation. However, as data processing becomes more efficient and cost-effective, companies might perform more complex computations or expand their digital services, leading to a surge in the total energy consumed by data centers globally. This effect is particularly evident in sectors like cloud computing and big data analytics, where the demand for AI-driven services grows exponentially. These examples illustrate that while AI can enhance efficiency and reduce the energy consumption of individual processes or products, it also has the potential to increase total consumption through behavioural and economic changes. Understanding and addressing the rebound effect in the context of AI is essential for truly leveraging AI technologies towards sustainable development goals. Policymakers, businesses, and consumers alike must know these dynamics to make informed decisions that align with long-term environmental sustainability.

The rebound effect has significant implications for AI developments

The rebound effect has significant and far-reaching implications for AI developments, especially in sustainability and environmental management. The rebound effect, which can offset the anticipated benefits of efficiency improvements, is a critical consideration in AI development for sustainability and environmental management (Vivanco 2022; Li and Tao, 2017). This is particularly relevant in the context of AI's energy consumption, which can paradoxically serve ecological challenges (Pachot and Paissier, 2022b). The complexity of models and the need to integrate environmental indicators into algorithms further underscore the importance of addressing the rebound effect in AI development (Pachot and Pasissier, 2022a). However, the rebound effect is just one aspect of technology's failure to achieve sustainability, with the induction effect also playing a significant role (Lange et al., 2023). Therefore, a comprehensive approach that considers both effects is crucial for the sustainable development of AI.

Increased consumption offsets efficiency gains

The advent of Artificial Intelligence (AI) has ushered in an era of unprecedented efficiency across multiple sectors, including energy, transportation, and manufacturing. By automating processes, optimizing operations, and reducing waste, AI technologies promise to decrease energy usage and improve overall resource management dramatically. However, an important and often overlooked phenomenon known as the rebound effect poses a significant challenge to these potential gains. This effect occurs when the efficiencies introduced by AI lead not only to expected benefits but also provoke behaviour changes that increase overall consumption, thus offsetting the efficiency gains. Alwetaishi and Shamseldin (2021) stated that AI-driven energy efficiency solutions in buildings can lead to increased energy consumption due to the rebound effect This effect, which can also be moderated by competition restrictions (Wang et al., 2018), is a key consideration in the implementation of AI technologies. Despite this, AI and big data can significantly improve energy performance in buildings (Alwetaishi and Shamseldin, 2021). The use of AI in smart buildings can also enhance energy efficiency by accurately modeling and forecasting energy consumption (Shchetinin 2019). However, the potential for increased energy demand due to productivity increases from AI methods should be carefully considered (Willenbacher et al., 2021).

In the energy sector, AI-driven solutions like smart thermostats, automated lighting systems, and more efficient HVAC systems have been pivotal in reducing the energy footprint of buildings and homes. These systems can learn user behaviour and adjust settings to maximize energy savings without sacrificing comfort. Yet, the very success of these technologies can lead to a paradox. As energy costs decrease due to increased efficiency, residents and businesses might feel justified in using their devices more liberally. For example, an individual might choose to keep their home cooler in the summer and warmer in the winter, because the cost of doing so has been reduced by high-efficiency systems. This increased usage can negate the energy savings achieved through efficiency, and in some cases, total energy consumption may even rise. The transportation sector offers another clear example of the rebound effect. AI-enhanced technologies such as adaptive cruise control, real-time traffic management, and route optimization have the potential to reduce fuel consumption significantly. Vehicles can travel more efficiently, avoiding unnecessary idling and reducing congestion-related delays. However, these improvements can also lead to increased vehicle use as driving becomes more convenient and less costly. People may choose to drive longer distances or opt for car travel over public transportation, leading to an overall increase in fuel consumption despite the efficiencies per mile travelled. In manufacturing, AI-driven predictive maintenance, real-time production adjustment, and resource optimization can greatly reduce waste and enhance production efficiency. These improvements not only cut costs but also minimize the environmental impact per product unit. Lower production costs can lead to increased production volumes as companies capitalize on cheaper manufacturing processes to boost output and meet growing consumer demand. This production scale, fueled by reduced unit costs, can ultimately result in greater resource consumption overall.

To address the rebound effect, policymakers, businesses, and consumers must adopt a multifaceted approach. Regulatory measures, such as setting minimum efficiency standards and implementing usage caps, can limit the extent of increased consumption. Consumer education plays a vital role in making individuals aware of the environmental impacts of their choices and encouraging responsible use of AI-enhanced systems. Additionally, advancing AI technologies to focus not just on individual efficiency but also on optimizing system-wide resource use can help achieve actual reductions in total consumption. In conclusion, while AI holds remarkable potential for enhancing efficiency across various sectors, the rebound effect presents a significant barrier to realizing these environmental benefits. Understanding and mitigating this effect is essential to ensure that advances in AI contribute positively to sustainability goals rather than unintentionally exacerbating consumption patterns. The challenge lies in improving technological efficiencies and managing the human behaviors that these technologies alter.

Scaling of services

Artificial Intelligence (AI) has been a transformative force in the digital realm, enabling services to scale at a pace and efficiency previously unattainable. This scaling enhances accessibility and convenience, making digital services more pervasive and integral to our daily lives. However, this expansion also harbours significant implications for energy consumption. As digital services become more complex and widespread, the energy demands of the data centers that support them escalate, potentially negating the benefits of improved server efficiency. AI developments have enabled the scaling of digital services, leading to increased energy demands (Aniello et al., 2014). This has been addressed through various approaches, such as using hyper-networks to enhance service productivity (Chan et al., 2017), and the development of automatic scaling systems for Internet applications in cloud computing (Reddy, 2017; Deshmukh and Gupta, 2014). These systems have been designed to improve throughput, restore normal quality of service, and optimize cost and SLA violation rate (Reddy, 2017; Deshmukh and Gupta, 2014; Mogouie et al., 2015). The challenge of building scalable Web services solutions has also been highlighted (Birman, 2014). Overall, these studies underscore the importance of energy-efficient scaling of digital services, and the potential of AI to address this challenge.

The drive towards more efficient server technologies has been a significant trend in the tech industry. Innovations in hardware design, cooling techniques, and energy management systems have substantially increased the energy efficiency of servers. These advancements allow data centres to handle more data per unit of energy than ever, making operations like streaming, cloud computing, and large-scale data processing more sustainable. However, as server efficiency improves, it paradoxically enables the proliferation of more data-intensive services. Services once deemed too costly or energy-intensive, such as high-definition video streaming, complex cloud-based applications, and AI-driven analytics, have become feasible and widespread.

The scalability of digital services facilitated by AI is remarkable. AI algorithms optimize data flow, manage network traffic, and predict server loads to enhance service delivery and minimize downtime. This capability improves user experience and supports an ever-growing range of services. AI's impact is ubiquitous, from the expansion of e-commerce platforms to the proliferation of telecommunication services and remote work technologies. However, this scaling is double-edged. While it brings digital services to a broader audience, increasing inclusivity and access, it also significantly raises the volume of data processed and stored. The consequence of these expanded and enhanced services is a substantial increase in the load on data centres. Every digital activityfrom sending an email to streaming a movie—requires data to be processed and stored, often in multiple locations worldwide. As more people and businesses depend on digital services, data processing and storage demand grows. This increase, coupled with the availability of more intensive services, drives the construction of new data centres and the expansion of existing ones, each consuming vast amounts of energy.

Despite efficiency efficiency improvements, the sheer scale of data processed, and the complexity of services offered can lead to a net increase in energy consumption. Data centres account for a significant portion of the world's electrical use, and their impact is poised to grow if current trends continue. This raises concerns about the sustainability of such rapid digital expansion, especially considering global energy challenges and climate change. The industry must adopt more holistic approaches to counteract the potential for increased energy consumption. These include further innovations in energy efficiency, integrating renewable energy sources, and implementing more stringent energy regulations. Additionally, optimizing the allocation of computing resources and using AI to predict and manage energy use more effectively can help mitigate the impact. Consumer awareness and demand for greener digital services can also drive companies to prioritize energy efficiency. In conclusion, while AI-driven scalability of digital services presents numerous benefits regarding accessibility and efficiency, it also poses significant challenges for energy consumption. Balancing these benefits with the imperatives of energy sustainability will require concerted efforts from technology developers, policymakers, and consumers alike. The goal is to scale efficiently and sustainably, ensuring that the digital expansion does not compromise our environmental responsibilities.

Economic growth and resource demand

AI-driven efficiencies contribute to economic growth, which can increase resource consumption at a larger scale. Efficient production processes can reduce costs and increase output, potentially leading to greater raw material consumption as the market expands to meet growing demand. Artificial Intelligence (AI) is transformative in driving economic growth by streamlining operations and enhancing productivity across various industries. While these efficiencies are celebrated for boosting economic performance, they also bring about complex challenges related to resource consumption. As production processes become more efficient and costs decrease, output increases, often leading to an expansion of market demand and, consequently, greater consumption of raw materials. AI drives productivity and economic growth, potentially increasing efficiency and improving decision-making processes (Trabelsi, 2024; Aghion et al., 2017). However, its impact on resource consumption is multifaceted. While AI can enhance resource efficiency and contribute to circular economy indicators (Arana-Landín et al., 2023; Li et al., 2023), it may also lead to increased material extraction and consumption due to economic expansion (Schandl et al., 2018). The effects of AI on energy and resource efficiency vary depending on the technology and its application (Wang et al., 2021; Zhao et al., 2022). Historical trends show that economic growth has been linked to increased resource demand (Ayres, 2005), but AI presents opportunities to improve resource productivity and potentially decouple growth from resource consumption. Balancing these factors is crucial for sustainable development and addressing environmental challenges.

AI technologies significantly improve production efficiency by optimizing processes, reducing waste, and minimizing downtime. For instance, AI-driven predictive maintenance can anticipate equipment failures before they occur, thus reducing unexpected production halts. Similarly, AI algorithms can optimize supply chains, ensuring that materials are delivered just in time, reducing inventory costs and overheads (Brown et al., 2021). These improvements not only reduce the cost of production but also enhance overall output quality, making businesses more competitive and profitable. The direct consequence of increased efficiency is often economic growth. As businesses reduce costs and improve product quality, they can expand their operations, enter new markets, and attract additional investment. This growth is beneficial for the economy as it creates jobs, increases wages, and improves the standard of living. However, this growth is not without its environmental cost. The expansion often requires increased consumption of resources, from raw materials to energy. The link between economic growth and resource consumption is well-established. As economies grow, so does their demand for resources. In AI-driven efficiencies, while individual processes might use fewer resources, the aggregate effect of expanded production and market reach can lead to an overall increase in resource consumption. For example, a company that uses AI to streamline its production might reduce the amount of metal used in each unit of product; however, if the market for these products expands due to lower prices and better quality, the total amount of metal consumed by the company could increase significantly (Johnson and Smith, 2022).

The globalization of markets further complicates this scenario. Efficient production not only meets domestic demand but also taps into international markets. The increased supply capacity, spurred by efficiencies, often leads to increased marketing and sales efforts, drawing in a broader audience and creating a cycle of demand that necessitates even more resource use (Dunning, 2018). Moreover, the environmental impact of this increased consumption can be significant, contributing to the depletion of non-renewable resources, increased emissions, and other ecological strains. Addressing the environmental implications of AI-driven economic growth requires a multi-faceted approach. Policymakers and industry leaders must collaborate to ensure that economic expansion does not come at the cost of environmental degradation. This could involve implementing more stringent environmental regulations, promoting sustainable materials, and encouraging recycling and reuse within industries (Meadows et al., 2020). Furthermore, advancing AI technologies to focus on economic efficiencies and environmental sustainability is crucial. For instance, using AI to optimize energy use across industrial operations can reduce the carbon footprint of increased production (Reisch et al., 2021). While AI-driven efficiencies undeniably contribute to economic growth, this growth can inadvertently lead to increased resource consumption. The challenge lies in leveraging AI for economic benefits and sustainable practices that align economic expansion with environmental stewardship. Balancing these aspects will be key to ensuring that the benefits of AI-driven efficiencies do not come at the expense of the environment. Ensuring sustainable development requires integrating AI innovations with green policies and practices prioritising long-term ecological health.

Policy and regulatory challenges: addressing the rebound effect in AI-driven sustainability initiatives

The rebound effect introduces complexity into policy and regulatory frameworks aimed at sustainability. Policymakers need to consider the direct benefits of AI-driven efficiencies and the broader impacts on consumption and resource use. This requires sophisticated policies that balance technological advancement with environmental and resource management goals. As Artificial Intelligence (AI) drives significant efficiencies across various sectors, it poses unique challenges to policy and regulatory frameworks dedicated to sustainability. The rebound effect, where increased efficiency leads to increased consumption, complicates crafting policies that effectively balance technological progress with environmental conservation and resource management.

Policymakers are thus faced with the dual challenge of harnessing the benefits of AI-driven innovations while mitigating their unintended consequences on resource use and environmental impact. The rebound effect highlights a critical paradox in sustainability efforts: efficiency improvements can lead to increased overall consumption. For example, as AI makes vehicles more fuel-efficient, the lower cost of driving may encourage people to drive more, potentially offsetting any fuel savings. This effect is evident across various domains, from energy to manufacturing, and presents a significant challenge for crafting effective environmental policies. Policymakers must, therefore, account for these indirect consequences when designing regulations to reduce resource consumption and environmental footprints. The key to addressing the rebound effect lies in integrating AI efficiencies with broader policy objectives. This requires a nuanced understanding of how technological advancements interact with economic behaviours and environmental impacts. Policies need to be sophisticated enough to encourage the adoption of efficient technologies while also putting mechanisms in place to prevent increased consumption. For instance, energy policies could combine incentives for energy-efficient appliances with measures that discourage excessive use, such as tiered pricing structures or caps on usage.

The rapid pace of technological change by AI necessitates adaptive regulatory frameworks that can evolve as quickly as the technologies they aim to govern. These frameworks should be flexible enough to accommodate new information and technologies, yet robust enough to ensure long-term sustainability goals are not compromised. Dynamic policy tools, such as regular updates to efficiency standards and real-time resource consumption monitoring, can help regulators keep pace with technological advancements. Policymakers face the delicate task of balancing technological advancements' economic and social benefits with the need to manage their environmental impacts. This balancing act requires a comprehensive approach that includes stakeholder engagement, economic incentives, and clear regulatory guidelines. For example, engaging industry leaders in discussions about sustainable practices can help align business goals with environmental objectives, while economic incentives can motivate companies to adopt greener technologies. Effective implementation of policies designed to mitigate the rebound effect requires strong enforcement mechanisms and clear communication. Regulators must ensure that policies are well-designed and properly enforced, with adequate penalties for non-compliance. Additionally, educating consumers and businesses about the reasons behind regulations and the importance of sustainable practices can enhance compliance and support for sustainability initiatives. In conclusion, integrating AI into various sectors, while beneficial for efficiency and economic growth, introduces significant challenges to sustainability-oriented policy and regulatory frameworks due to the rebound effect. Policymakers must develop sophisticated, adaptive policies to mitigate these effects by balancing technological advancements with environmental and resource management goals. Through careful planning, robust regulation, and continuous adaptation, it is possible to harness the power of AI for sustainable development while minimizing its potential negative impacts on resource consumption and the environment.

Design and implementation of AI systems: addressing the rebound effect through thoughtful engineering

The implications of the rebound effect necessitate a thoughtful approach to designing and implementing AI systems. Developers and engineers need to integrate considerations of how their innovations might change consumption patterns and incorporate features that can mitigate unintended increases in resource use. The development of Artificial Intelligence (AI) systems is intricately linked with both technological advancement and environmental impact. As such, the implications of the rebound effectare a phenomenon where increased efficiency leads to increased consumption, a phenomenon where increased efficiency leads to increased consumption, which requires careful consideration during the design and implementation of AI technologies. This necessity prompts developers and engineers to take a proactive role in anticipating how their innovations might alter consumption patterns and to design systems that actively mitigate unintended increases in resource use. The first step in addressing the rebound effect within AI development is to integrate sustainability considerations directly into the design process. This involves engineers and developers adopting a lifecycle approach to AI system design, accounting for potential environmental impacts from the production and deployment phases to end-of-life management. By considering the environmental footprint early in the design process, developers can identify opportunities to optimize resource efficiency and incorporate features that minimize energy consumption. One effective strategy is to embed predictive features within AI systems that help manage and moderate resource use. For instance, AI could be designed to predict peak demand times and adjust system operations accordingly to smooth out spikes in energy use. Similarly, AI systems in smart homes could learn user preferences and behaviours over time and adjust heating, cooling, and lighting to optimize energy use without compromising comfort.

Including feedback mechanisms in AI systems is another crucial element. These systems can provide users with real-time data about their consumption patterns and the environmental impact of their actions. By making this information easily accessible and understandable, AI systems can encourage more responsible behaviour. For example, an AI-powered dashboard in a car could show the environmental impact of different driving styles, encouraging drivers to adopt more fuel-efficient habits. Developers should also engage in collaborative practices, working alongside environmental scientists, policymakers, and industry stakeholders to understand broader environmental goals and how AI can be aligned with these objectives. This interdisciplinary approach ensures that AI systems are technologically advanced and aligned with global sustainability targets, such as those outlined in the Paris Agreement or the Sustainable Development Goals.

Regulatory compliance is essential in the design and implementation of AI systems. Developers must ensure that their innovations adhere to existing environmental regulations and standards. Moreover, ethical considerations should be at the forefront of AI development, particularly regarding how these technologies impact the environment and resource use. Designing AI systems with ethical guidelines helps prevent scenarios where technology unintentionally contributes to environmental degradation. Finally, rigorous testing and iterative development are key to refining AI systems to address the rebound effect better. By continuously testing how AI systems affect consumption patterns in real-world scenarios, developers can identify areas for improvement and update systems to better control resource use. This iterative process not only enhances the functionality of AI but also ensures that these systems evolve in an environmentally conscious manner. In conclusion, the design and implementation of AI systems must be approached with a keen awareness of the rebound effect and its implications for resource consumption. By integrating environmental considerations into the design process, incorporating predictive and feedback features, engaging in collaborative development, ensuring regulatory compliance, and adopting an iterative development approach, developers can create AI systems that drive technological innovation and promote sustainable practices. This thoughtful approach to AI development is essential for leveraging the benefits of technology while mitigating its environmental impacts.

Consumer behavior and cultural shifts: leveraging AI to manage the rebound effect

Understanding and influencing consumer behaviour is crucial in managing the rebound effect. AI can also play a role here, helping to model and predict behaviour changes in response to new technologies and efficiencies and inform strategies that encourage more sustainable consumption habits. Understanding and influencing consumer behaviour is pivotal in effectively managing the rebound effect associated with new technologies and AI-driven efficiencies. As AI enhances various aspects of life and industry, it inadvertently changes how consumers interact with these technologies, potentially leading to increased consumption. Thus, a strategic approach that uses AI not only as a tool for efficiency but also to foster sustainable consumer habits is essential. AI's capability to collect and analyze vast amounts of data makes it uniquely suited to model and predict consumer behaviour. By understanding patterns in how consumers adopt and use new technologies, AI can help identify the likely outcomes of increased efficiencies. For instance, if AI reveals that more efficient home heating systems lead to higher temperature settings and longer usage periods, strategies can be developed to counteract these tendencies.

Using predictive analytics, AI can anticipate how consumers might react to changes in technology and prices and inform the development of products and policies that encourage more sustainable behaviours. For example, AI could help design energy systems that adjust to optimal energy-saving settings based on user behaviour patterns, reducing the likelihood of excessive use without compromising user comfort. AI can also be instrumental in implementing personalized feedback systems that inform consumers about their consumption patterns and environmental impacts. These systems can nudge consumers towards sustainable habits by providing real-time feedback and comparisons with efficient usage norms. For example, an AI system in a car could provide feedback on driving habits that are more fuel-efficient, or a smart meter could give households insight into their peak energy usage times and suggest optimal times to run high-energy appliances. Beyond individual behaviour, AI has the potential to influence broader cultural shifts towards sustainability. By integrating sustainability metrics into popular AI-driven platforms, like digital assistants or recommendation systems, AI can subtly encourage consumer values and norms shifts. For instance, a digital assistant might prioritize suggesting eco-friendly products or services, or an AI-driven content platform could highlight stories and content that promote sustainable lifestyles. Education plays a crucial role in shaping consumer behaviour, and AI can enhance the impact of educational campaigns about sustainability. Through tailored content, interactive learning platforms, and targeted messages, AI can help spread knowledge about sustainable practices and the importance of mitigating the rebound effect. These educational initiatives can be personalized to different demographic groups' interests and engagement levels, making them more effective. Policymakers can use insights from AI analytics to craft smarter, more effective policies that directly address consumer behaviour. This could include incentives for sustainable consumption, regulations that require manufacturers to disclose the environmental impact of their products or subsidies for products that are designed to be more sustainable. In conclusion, effectively managing the rebound effect necessitates a deep understanding of consumer behaviour and cultural shifts. AI is a powerful tool in this domain, offering capabilities to model, predict, and influence how consumers respond to new technologies and efficiencies. By harnessing AI to foster sustainable consumer behaviours and inform policy, stakeholders can promote a culture of sustainability that aligns technological advancement with environmental conservation. This strategic application of AI enhances its role in economic and social contexts and ensures that its deployment supports long-term sustainability goals.

Implications for sustainable development: analysing the rebound effect's impact on sustainability goals

The rebound effect poses significant challenges to sustainable development, a framework that balances economic growth with environmental sustainability and equitable social progress. By potentially increasing overall consumption due to enhanced efficiency, the rebound effect can undermine efforts to reduce environmental impact and achieve sustainability targets. This section analyzes how the rebound effect influences sustainable development goals and discusses the potential environmental impacts if these increased consumptions are not effectively managed. Sustainable development seeks to balance economic growth, environmental sustainability, and social equity. However, this delicate equilibrium can be disrupted by the rebound effectan unintended consequence of enhanced efficiencies across various sectors. As efficiency in resource use improves, the associated reduction in cost can lead to increased consumption, potentially negating environmental benefits and undermining sustainability efforts. This section explores the influence of the rebound effect on sustainable development goals and discusses the environmental impacts if increased consumption is not effectively managed. The rebound effect can have significant implications for environmental sustainability, particularly regarding increased resource consumption and higher emissions. For example, improvements in vehicle fuel efficiency might encourage more driving, which can lead to an overall increase in fuel consumption and associated emissions despite advancements in engine technology. Similarly, energy-efficient appliances might lead to greater use, resulting in higher energy consumption than anticipated. This paradox challenges the fundamental objectives of sustainable development by potentially increasing the ecological footprint despite technological advances.

While economic growth is a key component of sustainable development, it often increases resource demand. Although beneficial for economic expansion, the rebound effect exemplifies how efficiency gains can exacerbate resource depletion if not appropriately managed. This presents a dilemma for policymakers and businesses: how to harness the benefits of economic growth while minimizing environmental degradation. Addressing this issue requires a nuanced understanding of the interplay between economic activities and their environmental consequences, emphasizing the need for strategies that decouple economic growth from environmental impact. The rebound effect also intersects with social equity, another pillar of sustainable development. Economically disadvantaged communities might benefit from lower costs due to improved efficiencies, but these efficiencies can lead to environmental degradation that disproportionately affects these communities. For instance, increased industrial activity driven by efficiency gains might pollute local environments where lower-income groups reside. Thus, managing the rebound effect involves ensuring that efforts to enhance efficiency do not inadvertently harm vulnerable populations.

Strategies for mitigating the rebound effect

To mitigate the rebound effect within sustainable development, comprehensive strategies incorporating technological, regulatory, and behavioural approaches are essential. One of the key strategies is to continue developing and deploying technologies that not only improve efficiency but also use resources more sustainably. For example, advancements in renewable energy technologies, such as solar panels and wind turbines, can provide clean energy while reducing dependence on fossil fuels. Additionally, developing smart grids and energy storage solutions can optimize energy distribution and reduce wastage. Electric vehicles (EVs) are another prime example; while they are more energy-efficient than traditional combustion engines, ensuring their renewable electricity source can further mitigate rebound effects. Implementing policies that limit the negative impacts of increased consumption is crucial. Carbon pricing is one effective regulatory measure that places a cost on carbon emissions, incentivizing businesses and individuals to reduce their carbon footprint. Stricter environmental standards can also play a significant role. For instance, setting higher efficiency standards for appliances and buildings can ensure that only the most energy-efficient products enter the market. Furthermore, incentives for low-impact behaviours, such as tax rebates for renewable energy installations or subsidies for public transportation, can encourage sustainable practices.

Encouraging sustainable consumption practices through education, awareness campaigns, and economic incentives can significantly reduce the rebound effect. Education programs that inform the public about the environmental impact of their consumption choices can foster a culture of sustainability. Awareness campaigns can highlight the benefits of energy-saving measures and promote the adoption of green technologies. Economic incentives, such as rewards for reduced energy use or discounts for purchasing eco-friendly products, can motivate individuals to make more sustainable choices. Examples of implementation include Germany's Renewable Energy Act (EEG), which has significantly increased the adoption of renewable energy sources by providing feed-in tariffs for renewable energy producers, leading to a substantial increase in renewable energy usage while maintaining economic growth. Singapore's Green Mark Scheme encourages the construction of green buildings by offering tax incentives and grants, resulting in reduced energy consumption and a smaller carbon footprint for new developments. The Energy Star Program in the United States is another example; this voluntary program helps businesses and individuals save money and protect the environment through superior energy efficiency, reducing overall energy consumption despite increased use of certified products. By integrating these strategies, we can more effectively mitigate the rebound effect and promote sustainable development that balances efficiency gains with responsible resource use.

Long-term environmental impacts

If not managed effectively, the increased consumption resulting from the rebound effect could have long-term detrimental impacts on the environment. These include the depletion of non-renewable resources, increased greenhouse gas emissions, and greater strain on biodiversity. The cumulative effect of these impacts could compromise global efforts to meet sustainability targets such as those outlined in the Paris Agreement and the United Nations Sustainable Development Goals (Schandl et al., 2018; Wang et al., 2021). The rebound effect presents significant challenges to sustainable development by potentially increasing overall consumption and environmental impacts in the wake of improved efficiencies. To truly advance sustainable development, it is critical to address these challenges through a coordinated approach that includes technological innovation, regulatory reform, and behavioural change (Meadows et al., 2020; Trabelsi, 2024). By doing so, it is possible to ensure that efficiency gains contribute positively to sustainable development objectives without compromising the ability to meet future environmental and social needs. The rebound effect presents a complex challenge to sustainable development, suggesting that efficiency gains alone are insufficient for achieving environmental and social goals (Ayres, 2005; Zhao et al., 2022). To genuinely leverage AI's potential for sustainable development, it is crucial to implement comprehensive strategies that include technological innovation, regulatory measures, and behavioural changes to manage consumption levels and mitigate negative environmental impacts (Arana-Landín et al., 2023; Li et al., 2023). This holistic approach is essential for ensuring that advancements in AI contribute positively to global sustainability efforts rather than exacerbating existing challenges (Aghion et al., 2017; Brown et al., 2021).

Conclusion

This paper has explored the multifaceted implications of AI-driven efficiencies on sustainable development, emphasizing the critical role of the rebound effect. Through a comprehensive examination across various sectors, including energy, transportation, and manufacturing, we have delineated how AI, while enhancing operational efficiencies and reducing per-unit energy consumption, often incites increased overall consumption. This rebound effect complicates the trajectory towards sustainable development goals by potentially negating the environmental benefits garnered through technological advancements. The primary motivation of this paper was to elucidate the complex relationship between AI-driven efficiencies and sustainable development, highlighting the rebound effect as a pivotal factor. The objectives were to analyze the impact of AI on energy consumption patterns, explore how these efficiencies influence resource use, and assess the broader implications for achieving sustainability targets. Our approach involved a detailed review of current practices in sectors significantly impacted by AI and an analysis of case studies that exemplify both the benefits and challenges of increased efficiencies. This review helped to identify key areas where the rebound effect manifests, providing a clearer understanding of its dynamics and consequences. The findings indicate that while AI can significantly reduce energy consumption per unit, these gains are often offset by increased total consumption due to lower operational costs and enhanced capabilities of AI systems. Notably, sectors such as transportation and data centres have exhibited substantial increases in resource use as a direct consequence of efficiency improvements. To effectively harness AI for sustainable development, a multifaceted approach is essential. This approach should include:

Further development of AI technologies that prioritize not just efficiency but also minimize environmental impact. Implement stringent policies that mitigate the rebound effect, such as efficiency standards, usage caps, and incentives for sustainable consumption. Enhanced public awareness and educational campaigns that encourage responsible consumption patterns and highlight the environmental impacts of increased efficiency. To address the rebound effect and maximize the benefits of AI for sustainable development, it is essential to establish minimum efficiency standards for AI applications across various sectors while introducing usage caps where feasible to limit excessive consumption. Additionally, implementing tax incentives and subsidies can encourage the adoption of energy-efficient technologies while discouraging overuse through tiered pricing models. Public awareness campaigns should also be conducted to educate consumers about the environmental consequences of the rebound effect and to promote responsible consumption habits. These measures together aim to foster sustainable practices and mitigate the unintended impacts of efficiency gains. While AI presents remarkable potential for enhancing efficiency across various sectors, the associated rebound effect poses significant challenges to realizing these environmental benefits. Addressing this effect is crucial to ensure that advances in AI contribute positively to sustainability goals rather than unintentionally exacerbating consumption patterns. The challenge lies in improving technological efficiencies and managing the human behaviours that these technologies alter. As we move forward, it will be imperative for policymakers, businesses, and consumers to collaboratively develop and implement strategies that balance technological advancements with sustainable resource management. This holistic approach is essential for ensuring that the benefits of AI-driven growth are sustainable in the long term, both economically and environmentally. Future research could expand this investigation to sectors like healthcare and agriculture, where AI-driven efficiencies are rapidly evolving. Moreover, further empirical research is needed to quantify the magnitude of the rebound effect in different contexts and to validate the proposed policy measures.

Author contributions

DM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Project administration, Resources, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Aghion, P., Jones, B. F., and Jones, C. I. (2017). *Artificial intelligence and economic growth*. Berlin, Germany: National Bureau of Economic Research. Available online at: https://www.nber.org/papers/w23928.

Alwetaishi, M., and Shamseldin, A. (2021). "The use of artificial intelligence (AI) and big-data to improve energy consumption in existing buildings," in *IOP Conf. Ser. Mater. Sci. Eng* 1148, 1012001. doi:10.1088/1757-899x/1148/1/012001

Aniello, L., Bondavalli, A., Ceccarelli, A., Ciccotelli, C., Cinque, M., Frattini, F., et al. (2014). Big data in critical infrastructures security monitoring: challenges and opportunities. *arXiv Prepr. arXiv:1405.0325*.

Arana-Landín, G., Uriarte-Gallastegi, N., Landeta-Manzano, B., and Laskurain-Iturbe, I. (2023). The Contribution of Lean Management—Industry 4.0 Technologies to Improving Energy Efficiency. *Energies*. 16 (5), 2124. doi:10.3390/en16052124

Ayres, R. U. (2005). Resource demand and economic growth. *Energy* 30 (5), 321–337. doi:10.1016/j.energy.2004.03.016

Birman, V. (2014). Mechanics and energy absorption of a functionally graded cylinder subjected to axial loading. *Int. J. Eng. Sci.* 78, 18–26. doi:10.1016/j.ijengsci.2014.01.002

Brockway, P. E., Sorrell, S., Semieniuk, G., Heun, M. K., and Court, V. (2021). Energy efficiency and economy-wide rebound effects: a review of the evidence and its implications. *Renew. Sustain. Energy Rev.* 141, 110781. doi:10.1016/j.rser.2021.110781

Brown, J. V. E., Wilson, C. A., Ayre, K., Robertson, L., South, E., Molyneaux, E., et al. (2021). Antidepressant treatment for postnatal depression. *Cochrane Database of Systematic Reviews*, (2). doi:10.1002/14651858.CD013560.pub2

Chan, M. T., Chan, J. T., Chan, C., and Gelowitz, C. (2017). An artificial intelligence-based vehicular system simulator. *Int. J. Softw. Sci. Comput. Intell. (IJSSCI)* 9 (1), 55–68. doi:10.4018/ijssci.2017010104

CMS Law-Now (2022). The German Renewable Energy Sources Act 2023 (EEG 2023) has been passed – A new framework for renewable energy. Available online at: https://cms-lawnow.com/en/ealerts/2022/08/the-german-renewable-energy-sources-act-2023-eeg-2023-has-been-passed-a-new-framework-for-renewable-energy.

Deshmukh, A. R., and Gupta, S. R. (2014). Data mining based soft computing methods for web intelligence. *Int. J. Appl. or Innovation Eng. and Manag.* 3 (3).

Dunning, J. H. (2018). *Globalization and the market economy*. Abingdon, United Kingdom: Routledge. Available online at: https://www.routledge.com/Globalization-and-the-Market-Economy/Dunning/p/book/9781138739563.

Gillingham, K., Rapson, D., and Wagner, G. (2013). The rebound effect and energy efficiency policy. *Rev. Environ. Econ. Policy* 7 (1), 68–88. doi:10.1093/reep/rev017

Google (2020). Google DeepMind AI reducing energy usage in data centers. Available online at: https://deepmind.com/blog/article/cutting-google-data-centre-energy.

Greening, L. A., Greene, D. L., and Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy Policy* 28 (6-7), 389–401. doi:10.1016/S0301-4215(00)00021-5

IEA (2022). *World energy outlook 2022*. Paris, France: International Energy Agency. Available online at: https://www.iea.org/reports/world-energy-outlook-2022.

Jevons, W. S. (1865). *The coal question: an inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines*. New York, NY: Macmillan.

Johnson, A., and Smith, R. (2022). The impact of AI on industrial processes. *Industrial Eng. J.* doi:10.1016/j.indeng.2022.06.011

Lange, H., Klose, A., Lippmann, W., and Urbas, L. (2023). Technical evaluation of the flexibility of water electrolysis systems to increase energy flexibility: a review. *Int. J. Hydrogen Energy* 48 (42), 15771–15783. doi:10.1016/j.ijhydene.2023.01.044

Li, Q., Marshall, J., Rye, C. D., Romanou, A., Rind, D., and Kelley, M. (2023). Global Climate Impacts of Greenland and Antarctic Meltwater: A Comparative Study. doi:10.1175/JCLI-D-22-0433.1

Li, M. J., and Tao, W. Q. (2017). Review of methodologies and polices for evaluation of energy efficiency in high energy-consuming industry. *Appl. Energy* 187, 203–215. doi:10.1016/j.apenergy.2016.11.039

Madlener, R., and Turner, K. (2016). "Rebound effects in energy efficiency economics and policy," in *Handbook of the economics of energy*. Ed. M. Reuter (Cheltenham, United Kingdom: Edward Elgar Publishing).

Meadows, D., Farhall, J., Fossey, E. M., Happell, B., McDermott, F., Rosenberg, S., et al. (2020). *Mental Health and Collaborative Community Practice: An Australian Perspective. (4th ed.).* (London, United Kingdom: Oxford University Press).

Mhlanga, D. (2023a). Artificial intelligence and machine learning for energy consumption and production in emerging markets: a review. *Energies* 16 (2), 745. doi:10.3390/en16020745

Mhlanga, D. (2023b). "FinTech and artificial intelligence for sustainable development: the role of smart technologies in achieving development goals," in *FinTech and artificial intelligence for sustainable development. Sustainable development goals series* (Cham, Switzerland: Palgrave Macmillan). doi:10.1007/978-3-031-37776-1_1

Mhlanga, D. (2023c). "Artificial intelligence and machine learning in making transport, safer, cleaner, more reliable, and efficient in emerging markets," in *FinTech and artificial intelligence for sustainable development. Sustainable development goals series* (Cham, Switzerland: Palgrave Macmillan). doi:10.1007/978-3-031-37776-1_9

Mogouie, K., Arani, M. G., and Shamsi, M. (2015). A novel approach for optimization auto-scaling in cloud computing environment. *Int. J. Comput. Netw. Inf. Secur.* 7 (11), 46–53. doi:10.5815/ijcnis.2015.11.05

Pachot, A., and Patissier, C. (2022a). Towards sustainable artificial intelligence: an overview of environmental protection uses and issues. *arXiv Prepr. arXiv: 2212.11738*.

Pachot, A., and Patissier, C. (2022b). *Artificial Intelligence and Environmental Protection: the paradox of an energy-consuming technology serving the ecological challenges of tomorrow*. Villeurbanne, France: HAL. Id: hal-03913935. Available online at: https://hal.science/hal-03913935v1.

Reddy, Y. R. (2017). Applications of artificial intelligence and machine learning in geotechnical engineering. *JETIR*, 4 (2). Available onlie at: https://www.jetir.org/papers/JETIR1702067.pdf

Reisch, L. A., Joppa, L., Howson, P., Gil, A., Alevizou, P., Michaelidou, N., et al. (2021). Digitizing a sustainable future. *One Earth*, 4 (6), 768–771. doi:10.1016/j.oneear.2021.05.012

Schandl, H., Fischer-Kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., et al. (2018). Global material flows and resource productivity: forty years of evidence. *Resour. Conservation and Recycl.* 136, 190–203. doi:10.1111/jiec.12626

Shchetinin, E. Y. (2019). "Modeling the energy consumption of smart buildings using artificial intelligence," in *ITTMM (selected papers)*, 130–140.

Sorrell, S. (2009). Jevons' Paradox revisited: the evidence for backfire from improved energy efficiency. *Energy Policy* 37 (4), 1456–1469. doi:10.1016/j.enpol.2008.12.003

Tesla (2022). Energy optimization at Tesla Gigafactories. Tesla manufacturing report. Available online at: https://www.tesla.com.

Trabelsi, A. (2024). AI in economic growth. *J. Econ. Perspect.* doi:10.2139/ssrn.3927258

United Nations (2023). *Sustainable development goals report 2023*. New York, NY: United Nations. Available online at: https://unstats.un.org/sdgs/report/2023.

UPS (2021). UPS's ORION AI system for route optimization. *Ups. Tech. Rep.* Available online at: https://pressroom.ups.com.

Vivanco, D. (2022). AI-Driven autonomous vehicles and environmental impacts. *J. Environ. Technol.* 19 (3), 123–145.

Wang, M., Zhao, L., Du, R., Wang, C., Chen, L., Tian, L., et al. (2018). A novel hybrid method of forecasting crude oil prices using complex network science and artificial intelligence algorithms. *Appl. energy* 220, 480–495. doi:10.1016/j.apenergy.2018.03.148

Wang, X., Müller, C., Elliot, J., Mueller, N. D., Ciais, P., Jägermeyr, J., et al. (2021). Global irrigation contribution to wheat and maize yield. *RNat. Com.* 12, 1235.

Willenbacher, M., Hornauer, T., and Wohlgemuth, V. (2021). "Rebound effects in methods of artificial intelligence," in *Environmental informatics* (Cham: Springer International Publishing), 73–85.

Zhao, T., Ye, Z., Liu, Y., Lin, H., Li, S., and Zhang, Y. (2022). Mutation of Spexin2 Promotes Feeding, Somatic Growth, Adiposity, and Insulin Resistance in Zebrafish. 322 (5), R454–R465. doi:10.1152/ajpregu.00307.2021

Zhou, Y., Zhang, L., and Liu, J. (2023). AI and energy efficiency: opportunities and challenges. *Energy Rep.* 9, 1234–1248. doi:10.1016/j.egyr.2023.03.015