Overcoming 'Jevons' Paradox' in the Circular Economy: Is Blockchain a Threat or Solution to Climate Change?

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Abstract

Since the advent of the industrial revolution, innovation, and the efficiencies it provides, drives economic growth. From Industry 1.0-4.0, new technology deprecates the previous industry paradigm resulting in increases in production capacity; however, the economic correlate of efficiency to production capacity has driven economic performance at the expense of the environment. From the internal combustion engine to light bulbs to desktop PCs to the Internet, technological innovation consumes more energy as gains in efficiency are spent on increases in energy demands to higher demand. This 'Jevons paradox' characterises capitalism and the free market throughout the modern industrial age; there are few, if any, popular technologies, which, through their widespread adoption, result in synergistic and sustainable economic and environmental performance. Even so-called 'sustainable' technology, e.g., EVs, calculate the contribution to CE based on an economic / environmental 'balance'. To tip this balance in favour of the environment is the key to closing the CE loop; blockchain represents a feasible solution, but only if it is implemented broadly and deeply across the global SC in production and end of life extension. This paper conducts a thought experiment of BC implementation utilising information cascade as an accelerant to global BC adoption toward CE.

Keywords
Circular economy, Blockchain technology, Thought experiment, Information cascade, Climate change

1. Introduction
Extant literature indicates that the implementation of blockchain (BC) 4.0 (the application of distributed ledger technology to manufacturing and supply chain) represents a transition opportunity for achieving a circular, and consequently, a more environmentally sustainable, supply chain (Kouhizadeh et al. 2019; Böckel et al. 2021; Khan et al. 2022). This is due to the capability of BC's distributed ledger to ensure high-quality data, transactional knowledge, learning, and outcomes (Vogel et al. 2019; Leng et al. 2020; Park and Li 2021; Javaid et al. 2021; Jeon et al. 2022); the benefits can be applied to both economic and environmental ends (Khan et al. 2021; Khan et al. 2022; Kouhizadeh 2022). The objective of this paper is to examine the potential for BC to achieve both economic and environmental performance, but only when the two are co-implemented; as with all previous disruptive industry technologies, BC is not immune to the Jevons Paradox, i.e. efficiency gains in industrial practice are directed toward more production such that the corresponding increase offsets and surpasses any inherent environmental benefits per unit of production (Giamietro and Mayumi 2018; Howson 2021; Yu et al. 2022) . A formula is developed and tested in a best-case and worst-case scenario in BC's implementation in Industry 4.0. The hypothesis of this paper is that information cascade, i.e. 'herd behaviour', has a negative mediating effect on the environmental performance of BC due to its triggering of negative externalities associated with game theory.

In contradistinction to the Jevons Paradox, an environmental 'Kuznet's Curve' occurs when efficiencies in production over time are enough to reduce the overall environmental impact (Wei 2015; Koilo et al. 2019). As BC evolves from 3.0 to 4.0 (BC evolution is summarized in Table 4. below), the quantity and quality of its implementation in Industry 4.0 will determine its support of CE, as the gains from efficiencies support either a Kuznet's Curve or a Jevons

Paradox. Whilst the latter directs efficiencies toward greater economic performance, the former redistributes efficiencies gained toward both economic and environmental performance; ‘The Kuznets curve has been applied in environmental pollution . Scholars find that many countries, including China, do go through such a Kuznets’ process’ (Wei 2015, p. 2).

The problem is that despite of what, for lack of a better term, might be called the Kuznets effect (when industry efficiencies converge toward environmental performance), global CO2 emissions (and GHGs more generally speaking) have continued to rise significantly each year. As carbon emissions are linked inextricably to climate change (global warming), this means that to slow and reverse global warming, industry needs first to slow and reverse the Jevons Paradox. Although scholars have previously suggested de-growth as the most logical strategy for reducing emissions, i.e. produce less, therefore pollute less (Trainer 2020; Pineault 2020; Tamesgen 2021), it may be a risky strategy to depend alone on reducing industrial output as this is likely to be hindered by the 'political and social unpalatability of degrowth’ (Alexander 2020, p. 16); degrowth ‘ignores the structural imperative for capitalists to pursue profit despite any costs they might impose on others’ (Ibid., p. 44). Although distributed ledger has previously been suggested as a facilitator for infrastructure for degrowth projects (Howson 2021), the question remains, how can BC adoption at once support the economy and environment when studies suggest that income growth (an indicator of increased industrial output) is linked to higher CO2 emissions (Ha and Byrne 2019; Liu et al. 2019)?

To wit, BC 4.0 has the potential to support economy and environment by encouraging a Kuznets curve which is characterized by efficiencies that are proportionate to increases in production. Eventually, the goal would be to create scalable CE and net zero such that economic growth no longer produces any deleterious environmental effects. This is the point of CE: to create as near a 100% capture and re-capture of energy and resources circulating in the economy (Winans et al. 2017; Morseletto 2020; Temesgen et al. 2021). According to scholars, BC’s role in achieving CE in Industry 4.0 (and 5.0) is critical due to the capability of distributed ledger to increase traceability, reliability and security, as well as synchronise the transaction processes and cost efficiencies in the supply chain (Kouhizade et al. 2019; Shojaei et al. 2021; Erol et al. 2022). As such, this paper sees ‘full switch theory’ (Tàbara 2018) and ‘information cascade theory’ (Rich 2022) as two mutually dependent factors to overcome the Jevons paradox and facilitate a Kuznets curve which prevents reaching negative ‘tipping points’ in the environment from which we cannot recover (Hansen 2007; Tàbara 2018; Armstrong et al. 2022).

Two research questions are asked in this paper:

RQ1: Will Blockchain 4.0 (BC 4.0) support a Kuznets Curve or induce a Jevons Paradox in manufacturing and supply chain?
RQ2: How does the effect of information cascade influence the BC 4.0 implementation toward CE performance?

In our exploration of RQ1, we hypothesise that BC 4.0 might worsen climate change if the rise in carbon emissions due to increased production outweighs the efficiencies it provides, thereby potentially triggering the Jevons paradox (da Rosa Righi et al. 2020). In addressing RQ2, we investigate the evolution of BC from its 1.0 to 3.0 stages and leverage this understanding to predict the potential effects of BC 4.0 implementation, specifically examining the role of information cascade as a mediating variable toward CE (Rich 2022). We aim to examine the potential for information cascade to reduce Jevons paradox and therefore aid in the transition to a more circular and sustainable supply chain (Ajwani-Ramchandani et al. 2021; Böhmecke-Schwafert et al. 2022).

The literature review explores the historical narrative of industrial innovation and its environmental consequences from Industry 1.0-4.0 (also positing the state of global warming and its link to CO2 emissions). In addition, the economic and environmental performance of BC 1.0-3.0 is explored indicating that its track record to date is not environmentally positive, e.g. Bitcoin: ‘Bitcoin alone (one of the cryptocurrencies supported by blockchain) has a carbon footprint equivalent to the whole of Switzerland (Blair 2020, p. 3). We also delve into the effects of the negative externalities of information cascade on BC's performance from crypto currency to ubiquitous and global transactions which can take place with perfect accuracy at 1M / second (Mukherjee and Pradhan 2021, p. 42). This lays the foundation for a subsequent thought experiment that envisages both the 'Best Case' (the Kuznets curve) and 'Worst Case' (the Jevons paradox) scenarios for BC's impact on the CE. The results will help design a predictive model for this paper’s contribution, i.e. the creation of a 'Jevons’ scale’ factor in BC 4.0 adoption in Industry 4.0 via creating a predictive model of the influence of information cascade as a mediating variable toward CE.

2. Literature Review

2.1 Industry 1.0-4.0 Environmental performance

Jevons Paradox, a concept named after the 19th-century economist William Stanley Jevons. Jevons observed that as technological improvements increase the efficiency of resource use, it tends to increase the consumption of that resource instead of reducing it (Everett 2001). This paradox is attributed to the fact that efficiency often leads to lower costs and higher demand. In the modern context, Jevons Paradox represents the dual edge of technological advancements: while innovation drives economic growth, it concurrently imposes a strain on finite resources and environmental sustainability (Everett 2001; Fagan 2011).

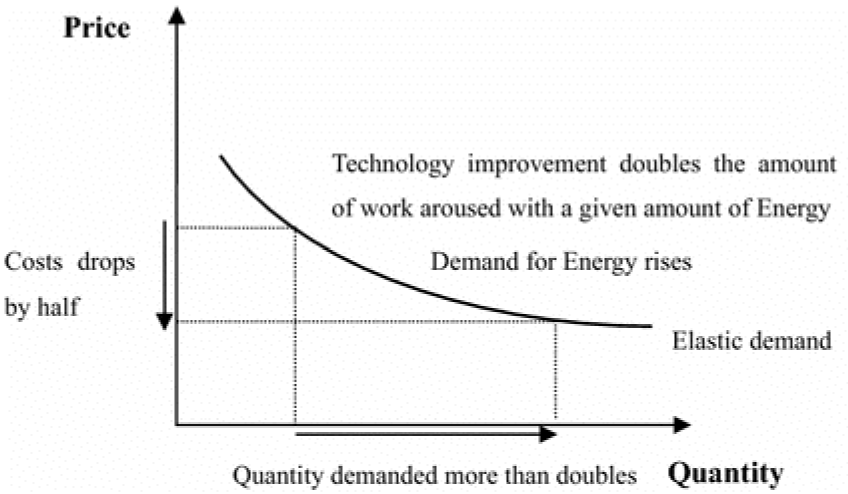

Figure 1. Jevons Paradox (2007**).** Source: Public Domain

However, the Kuznets Curve below (Fig. 2) provides a potential mitigation to Jevons paradox insofar as it shows the relationship between industrial growth and environmental performance as a Bell Curve. This effectively means that as GDP per capital increases, the per capita damage to the environment decreases. However, scholars have not found convincing evidence to support the theory's implication that raising GDB decreases emissions overall (Luzzati and Orsini 2009; Yandle and Bhattarai 2002).

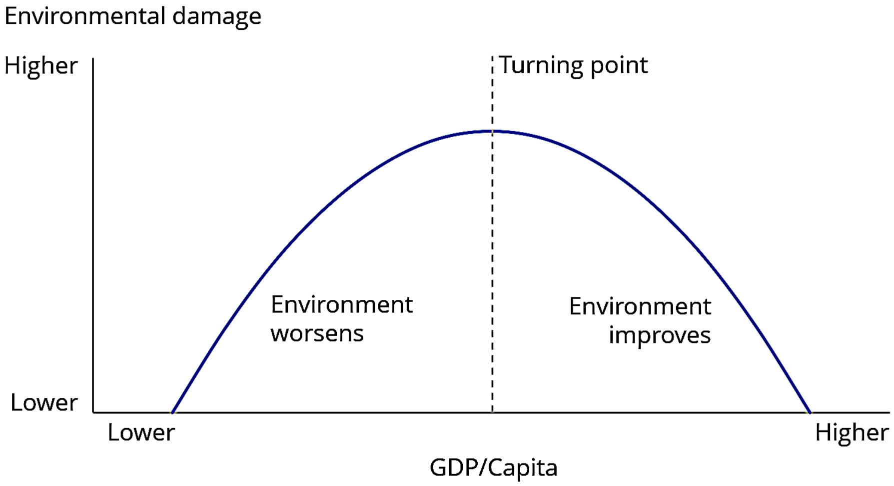

Figure 2. Environmental Kuznets Curve. Source: Public domain

The Kuznets Curve theory posits that economies initially increase greenhouse gas emissions due to industrial growth but later decline as they transition to service-based industries, adopting environmental regulations and technologies (Syed 2019). However, this does not account for 'imported emissions' from outsourced manufacturing (Syed 2019). Adding a nation's direct emissions to their imported emissions provides a fuller picture of their CO_2 contribution (Jiang et al. 2022; Khan et al. 2020; Baumert et al. 2019). Hence, Kuznets Curve can inadvertently result in higher CO2 emissions due to negative externalities associated with global GDP growth (Yandle 2002; Luzzati 2009; Madani 2020; Freire-González 2021).

2.2 Significance to Climate Change

Drawing from the Kuznets Curve's implications, we introduce Figure. 3, Table 1, and Figure. 4, each presenting data that raises significant questions regarding production levels, emissions, and global warming.

Figure. 3, a graphical depiction of global CO_2 emissions from fossil fuels, vividly illustrates that rising industrial growth doesn't necessarily correspond with declining emissions. The persistence of high emissions over time, even amid advances in production efficiency, implies a Jevons Paradox scenario, refuting the Kuznets Curve's optimistic outlook.

Table 1 provides a comparison of global warming in the USA and the EU along with global GHG emissions. The continuing rise in global emissions, despite variations in regional industrial activities and policy efforts, emphasises that increased production hasn't led to reductions in emissions. This lends further support to the idea of a Jevons Paradox at play.

Figure 4 presents the Global Land-Ocean Temperature Index, signaling the alarming consequences of unabated greenhouse gas emissions. The consistent upward trend in global temperatures underscores the urgency of intensifying CE initiatives to mitigate climate change.

These data reinforce the need for urgent, concerted efforts towards accelerating and deepening CE activities. The assumption that increased production efficiency alone will lead to a decrease in emissions is visibly flawed; a paradigm shift towards sustainable practices is a necessity.

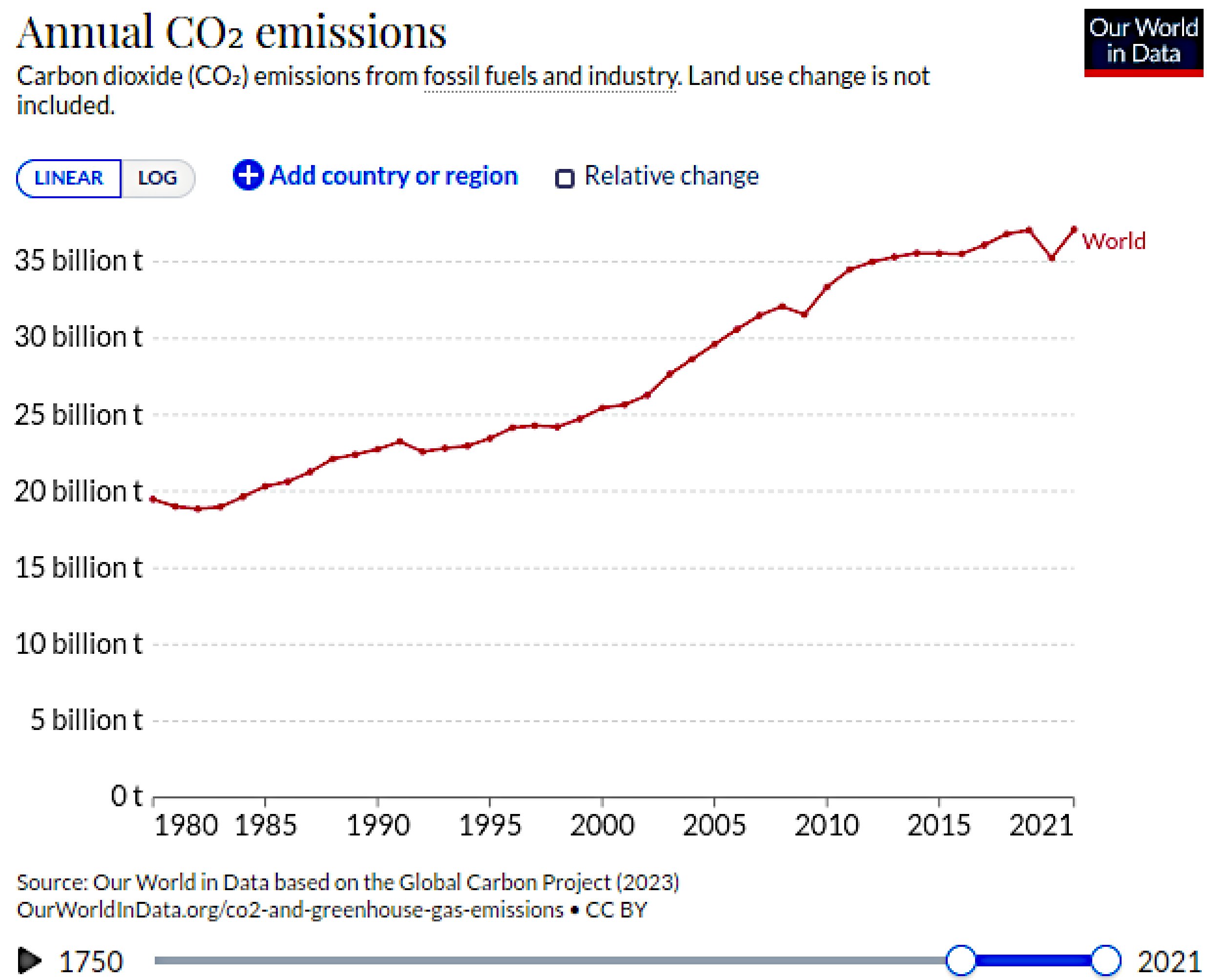

Figure 3. Global CO_2 emissions from fossil fuels. Source: Our World In Data.

Table 1. Global warming in USA and EU and global GHG emissions.

Aspect	**United States**	**European Union**	**Global**
Temperature in 2019	0.7°F (0.4°C) above 20th century average	Second warmest on record, 0.04°C cooler than 2018	N/A
Records in 2019	Third highest number of cooling degree days since 1950	New national July temperature records in Belgium, Germany, Luxembourg, Netherlands, and UK; Netherlands set all-time max of 40.7°C	N/A
Emission Growth Rate in 2019	Null	Null	1.1% (same as average since 2012)
Forest Fire Emissions in 2019	Null	Null	70% higher than in 2018

Decadal Growth (2004-2011)	Null	Null	2.9% average annual growth in GHG
Heating Degree Days in 2019	0.7% higher than in 2018	Null	N/A
Global GHG emissions	Null	Null	Increased from 24.5 GtCO2 eq in 1970 to 52.4 GtCO2 eq in 2019

Source: Olivier et al. (2017, p. 16-17)

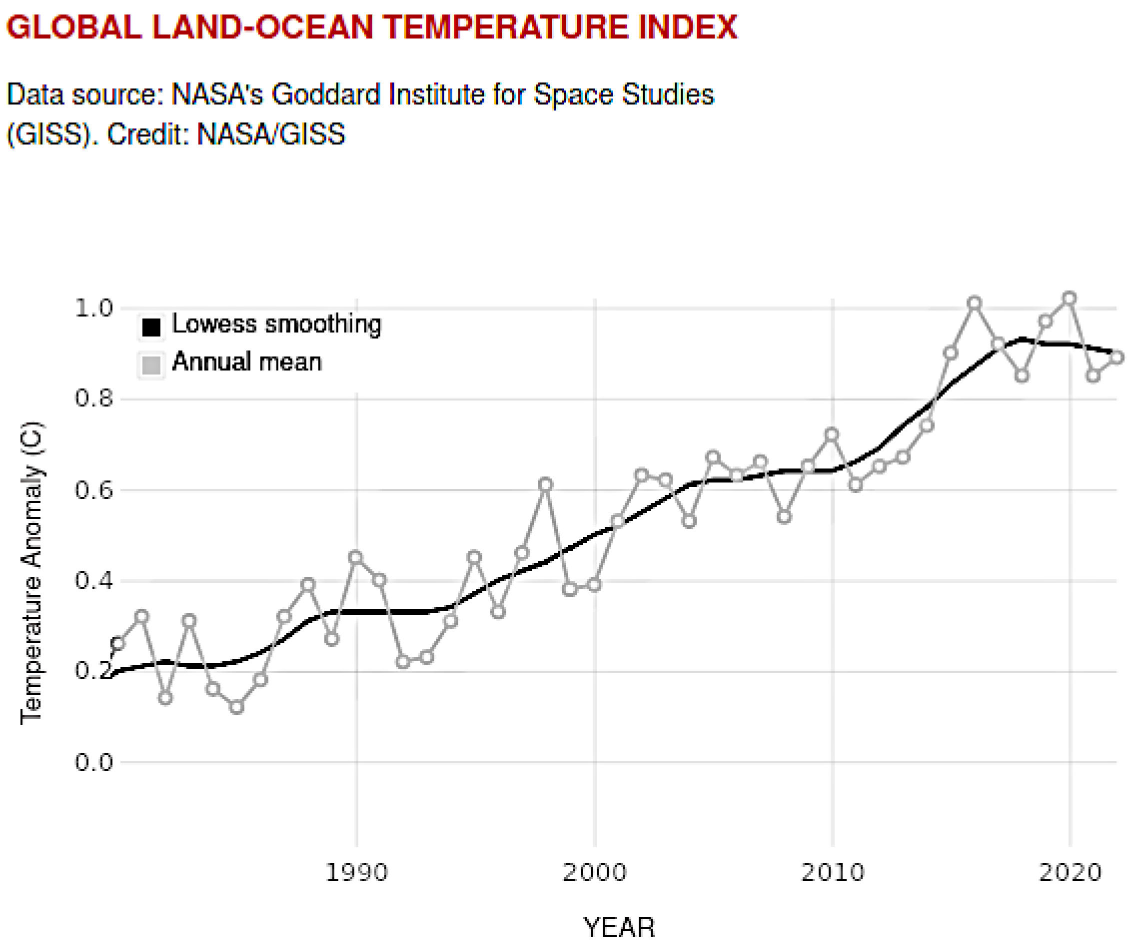

Figure 4. Global Land-Ocean Temperature Index**.**
Source: NASA's Goddard Institute for Space Studies.

According to UN.org (2023) climate change, largely caused by human-induced greenhouse gas emissions, represents an urgent global crisis. The rapid increase in temperatures, leading to the warmest decade on record, has severe consequences: from extreme weather events and compromised biodiversity, to impacts on global health, food security, and housing. Vulnerable populations bear a disproportionate burden of these effects. If unchecked, this could lead to a catastrophic 4.4°C increase by century's end. Immediate action to reduce emissions, adapt to climate impacts, and financially support these changes, including the transition to renewable energy, is crucial. High-emission countries bear a particular responsibility in this global response to ensure a sustainable future.

Table 2. Industry 1.0 to 4.0 and Greenhouse Gas (GHG) emissions.

Criteria	**Industry 1.0**	**Industry 2.0**	**Industry 3.0**	**Industry 4.0**
Major Technology Breakthrough	Steam Engine	Electricity	Computers, Internet	Block chain, Internet, AI
Notable Efficiency Gains to Society	Mechanization of Production	Mass Production	Digitalization, Automation	Automation, Optimization, Connectivity
Projected Profit (Global GDP Rise)	Significant Increase	Substantial Increase	Significant Increase	Substantial Increase
GHG emissions	High Carbon Emissions	Increased Energy Consumption	Electronic Waste	Potential for Lower Carbon Footprint
Total Effects on Climate Change	Significant Impact	Impact on Energy Consumption	Electronic Waste Disposal	Potential for Positive Contribution

Source: Olivier (2017); Yin (2018); Taskinsoy (2019); Lau (2020); Kumar (2020).

Yoro and Datamola's (2020) report highlights a 1.9% surge in global CO_2 emissions in 2019 compared to 2018, amounting to 55.6Gt, including land-use change emissions. Fossil fuel combustion accounts for around 72% of the increase. The report also notes an uptick in emissions of other greenhouse gases like methane, nitrous oxide, and fluorinated gases. These trends coincide with 2019 being one of the five warmest years since 1880 and the early occurrence of Earth Overshoot Day in the same year. This alarming data points to the urgent need for a 'full switch', as suggested by Tàbara (2018), requiring a radical shift in energy consumption, technology, and societal norms toward complete sustainability. This strategy could delay Earth Overshoot Day and mitigate the escalating climate crisis.

2.3 The Economic and Environmental Performance of BC 1.0-4.0

This study reviews the historical, economic, and environmental trends of industrial innovation and Blockchain (BC) development, from Industry 1.0 to 4.0, and BC 1.0 to 3.0 respectively, considering the information cascade effect (Xu, Chen, & Kou 2019; Maesa & Mori 2020; Terzi et al. 2019; Anjum et al. 2020; Javaid et al. 2021). It paves the way for envisioning BC's potential influence on a CE, modeling the 'Jevons' scale' effect on BC 4.0 adoption.

BC has evolved from enabling cryptocurrencies (BC 1.0) to supporting smart contracts (BC 2.0), and diversifying into sectors like healthcare and voting systems (BC 3.0). The upcoming BC 4.0 is projected to gain about 30% industrial adoption by 2023 (Kahn et al.). Our focus lies in BC 4.0's potential in manufacturing and supply chains, improving their transparency and traceability (Wang et al. 2020; Liu et al. 2020). BC's integration with IoT and AI could enhance smart city frameworks, reinforcing Industry 4.0 (Wu, Dai, & Wang 2020; Lee, Azamfar & Singh 2019).

BC's potential to revolutionise various sectors is attributed to its decentralization, transparency, and immutability (Xu et al. 2019). This technology promotes supply chain transparency, efficiency, and sustainability (Kouhizadeh, Sarkis, & Zhu 2019; Wang et al. 2020).

In conclusion, BC's integration into a CE could transform environmental performance (Kouhizadeh, Sarkis, & Zhu 2019; Böckel et al. 2021). However, the risks include direct emissions from electricity used in Proof of Work systems and e-waste from connected smart devices. Table 4. BC 1.0 to 4.0 and GHG emissions.

Table 3. BC 1.0 to 4.0 and GHG emissions.

Criteria	**BC 1.0**	**BC 2.0**	**BC 3.0**	**BC 4.0**
Main Application	Cryptocurrency	Smart Contracts	Decentralized Applications	Industry Integration
Company / Brand / Currency	Bitcoin	Ethereum	EOS	Hyperledger Fabric
Profit Description	Early adoption and	Decentralized	Tokenization and	Enterprise BC

	trading	finance (DeFi)	ICOs	solutions
Proof of Work/Stake	Proof of Work	Proof of Stake	Delegated Proof of Stake	Various Consensus Mechanisms
Attached Industry Carbon Footprint	High	Moderate	Variable	Potential for Lower Carbon Footprint

Source: Khan (2019); Howson (2021); Mukherjee (2021); Mourtzis (2023); Zhang et al. (2023).

In fact, there are solutions to each of these issues, for example, using proof of stake systems which require less computational power (less than 1% of the energy consumption) to operate and therefore less energy demands (Khan 2019; Howson 2021; Mukherjee 2021; Mourtzis 2023). This is important as Bitcoin, a proof of work cryptocurrency powered by BCT, has generated huge demands for energy:

'Most authors have found that Bitcoin mining generates a significant amount of CO2 (e.g., Corbet et al. 2019). Jiang et al. (2021) show that in 2020, Bitcoin mining contributed approximately 1 % to the global CO2 emissions and that the average CO2 emissions per unit of power generation in China was approximately 570 g. They argue that if there are no feasible policies or government interventions, the total annualized energy consumption of the Bitcoin blockchain in China is expected to reach a peak of 296.59 TWh in 2024, with emissions of approximately 130.5 million metric tons of CO2 equivalent. This accounts for approximately 5.41 % of China's total carbon emissions from power generation' (Zhang et al. 2023).

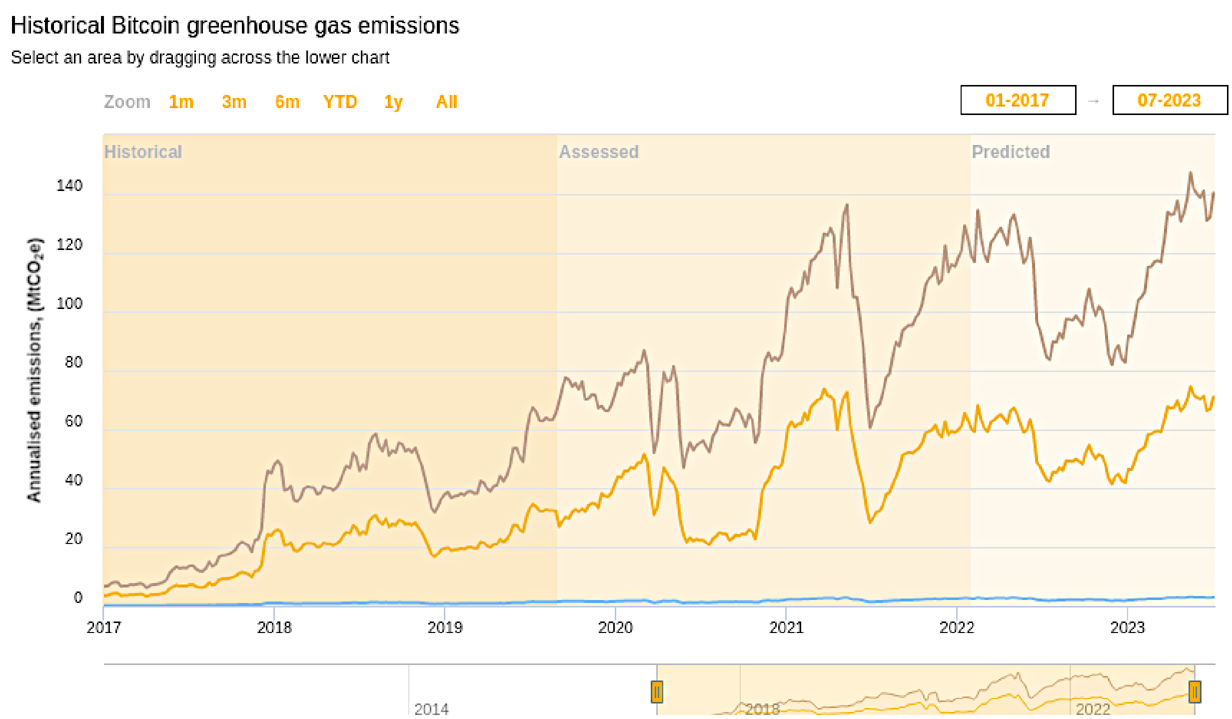

Figure 5. Historical Bitcoin greenhouse gas emissions (GHG).
Source: Cambridge Bitcoin greenhouse gas emissions.

How can BC solve GHG emissions in its 4.0 form? This can be answered first by considering Yoro and Daramola (2020)'s study of CO2 and GHG emissions and their primary sources of 1. Power generation 2. Cement industry, 3. Petrochemical plants, and the 4. Iron and steel industries. Below is a table in which the first two rows are informed by Yoro and Daramola (2020), but also combined with literature which further links BC to each solution.

Summary of potential Benefits of BC in CE

- Traceability and Transparency: BC can provide transparent and traceable records of products and materials throughout their lifecycle (Wang et al. 2020). This enhances accountability and can be pivotal in verifying the origin, authenticity, and environmental impact of products (Kouhizadeh et al. 2019; Khan et al. 2022).
- Efficient Asset Management: Through tokenisation, physical assets can be digitally represented in BC (Narayan & Tidström 2020). This facilitates efficient management of assets, enabling their sharing, leasing, or selling, contributing to the extended use of products and materials in CE (Liu et al. 2020; Ajwani-Ramchandani et al. 2021).
- Smart Contracts for Automated Compliance: BC enables the use of smart contracts that execute transactions when predefined conditions are met (Terzi et al. 2019). In CE, smart contracts can be used to ensure automated compliance with recycling or resource usage standards (Vogel et al. 2019).
- Enhanced Circular Supply Chains: BC can facilitate seamless information sharing across supply chains (Wang et al. 2020). In CE, this can enable better coordination among stakeholders for recycling, refurbishment, and responsible sourcing (Kouhizadeh et al. 2022; Nandi et al. 2021).

Case Studies of BC Implementation in CE

- De Beers' Tracr: De Beers, a diamond company, launched Tracr, a BC platform that tracks the provenance of diamonds. It ensures that the diamonds are conflict-free and sourced sustainably, supporting CE principles (Cartier et al. 2018; Smits and Hulstijn 2020).
- Plastic Bank: Plastic Bank uses BC to incentivise plastic waste collection (Howson 2021; Ajwani-Ramchandani et al. 2021). Individuals can exchange collected plastic for BC-secured tokens, which can be used to purchase goods and services (Ajwani-Ramchandani et al. 2021). This initiative tackles plastic pollution while promoting recycling and reuse.
- Provenance for Sustainable Fishing: Provenance, a BC platform, is used to track and verify the sustainability and fair-trade practices in the fishing industry. It enables consumers to have access to verified information about the source and impact of the products (Magrini et al. 2021).

Challenges and Limitations of BC in CE

- Scalability: The large-scale application of BC in CE might be hindered by scalability issues (Wu et al. 2020). Some BC networks face limitations in handling many transactions, which can be critical in global supply chains (Chauhan et al. 2022).
- Energy Consumption: Public BC networks, particularly those using proof-of-work consensus mechanisms, consume significant amounts of energy, which is counterproductive to the environmental sustainability goals of CE (Rejeb et al. 2022).
- Data Privacy and Security: Despite BC's security features, concerns regarding data privacy persist, especially when sensitive information is involved (Maesa & Mori 2020). Moreover, the immutable nature of BC makes error rectification challenging (Böckel et al. 2021).
- Legal and Regulatory Hurdles: The integration of BC in CE may face legal and regulatory challenges, as governments and institutions are yet to fully understand and regulate BC technologies (Böhmecke-Schwafert et al. 2022).

Possible Mitigations for the Challenges

- Adopting Scalable Solutions: Implementing BC solutions that are scalable, such as those using proof-of-stake or other consensus mechanisms, can address scalability issues (Wu et al. 2020). Layer 2 solutions like sidechains can also enhance scalability (Leng et al. 2020).
- Energy-efficient Consensus Mechanisms: Shifting from energy-intensive consensus mechanisms like proof-of-work to more energy-efficient alternatives such as proof-of-stake can mitigate the energy consumption concern (Rejeb et al. 2022).
- Privacy-preserving Techniques: Implementing privacy-preserving techniques such as zero-knowledge proofs can help maintain data privacy on BC networks (Maesa & Mori 2020).
- Collaboration with Regulators: Engaging with regulatory authorities to develop a legal framework that supports BC integration in CE is vital (Böhmecke-Schwafert et al. 2022). This involves education, dialogue, and collaboration between industry stakeholders and policymakers.

In summary, BC holds immense potential as a catalyst in CE, with benefits including enhanced traceability, efficient asset management, and streamlined supply chains (Kouhizadeh et al. 2019; Wang et al. 2020). While challenges such as scalability, energy consumption, and regulatory hurdles exist, they can be mitigated through scalable solutions, energy-efficient consensus mechanisms, privacy-preserving techniques, and collaboration with regulators (Böckel et al. 2021; Böhmecke-Schwafert et al. 2022).

2.4 The Effects of Information Cascade on BC's Performance

An information cascade occurs when individual investors have access to private information. Since the decision reveals to sequential investors, the posterior probability of belief in the actual market state leads toward the same decision. The more superior the information is, the acceleration of the cascade becomes faster. However, the model may lead to a dangerous consequence. First, the initial signal can be wrong but lead the market. Second, as other influential sign reveals that exceed the reliability of the previous one can overturn the situation. Third, even the superior signal can be based on imperfect information (Easley & Kleinberg 2010). The fall of dogecoin shows how fragile the up/down market cascade can be under imperfect information delivered through social media (Kim 2021, p. 11).

Information cascades have played a significant role in the development and adoption of BCT through its different stages: BC 1.0 2.0, and 3.0. However, this has also been accompanied by volatility and some shortcomings in achieving its full potential in terms of environmental and economic performance.

BC 1.0 - Cryptocurrencies (Thompson 2020; Philippas 2020; Haryanto 2020): BC 1.0, typified by Bitcoin, gained attention through an information cascade ignited by early adopters' praise for its decentralization and security. Subsequent media narratives around wealth accumulation led to widespread, but often uninformed, investment, resulting in severe price volatility. The high energy consumption of BC 1.0's proof-of-work mining raised unforeseen environmental concerns.

- **BC 2.0 - Smart Contracts and Decentralized Applications (DApps)**: BC 2.0, embodied by Ethereum, expanded possibilities with smart contracts and decentralised applications, sparking a rush of speculative Initial Coin Offerings (ICOs). However, this rush led to a volatile market and many unfulfilled projects. Like its predecessor, BC 2.0 also raised environmental issues due to its reliance on a proof-of-work consensus mechanism.
- **BC 3.0 - Scalability, Interoperability, and Sustainability**: BC 3.0 aims to address some of the limitations of earlier versions by focusing on scalability, interoperability between different BCs, and sustainability. Projects like Polkadot, Cardano, and others represent this evolution. However, as with previous iterations, information cascades contribute to hype and speculation. This has sometimes detracted from meaningful development and adoption, as the focus is often on quick financial gains rather than on building sustainable and useful networks.
- **BC 4.0 - Application in manufacturing and supply chain management:** BC 4.0 intends to pioneer systems transformation via its unparalleled capabilities including enhancing transparency, efficiency and interoperability such as physically, digitalisation (Rejeb et al. 2021). BC is envisioned as a catalyst for a more sustainable, inclusive global economic landscape (Schwab 2021).

In summary, information cascades have contributed to the rapid but highly volatile development of BCT through its various stages. The speculation, driven by these cascades, often overshadows genuine innovation, leading to bubbles and crashes. Moreover, the environmental impacts were often sidelined in the initial euphoria, though they have since become a major concern and focus for improvement. It is essential for the BC community and investors to foster a more measured approach that emphasises sustainable development and genuine utility over speculation, to realise the full potential of BCT.

2.5 BC's Transformative Potential in CE

Traceability (or Visibility)

BC provides a transparent ledger documenting each step in the supply chain, recording every transaction and transfer of ownership (Kouhizadeh et al. 2019; Maesa et al. 2020). Traceability supports the CE by pinpointing inefficiencies and waste, facilitating better resource allocation, repurposing, and recycling (Khan et al. 2021; Shojaei et al 2021). In a study on BC's potential to make product deletion a circular process, Kouhizadeh et al. (2019, p. 8) note that 'BC can contribute to product deletion management by providing accurate and reliable information related to shared products and services'.

Reliability and Security

BC's decentralised structure and cryptographic processes (DSCP) ensure data security and integrity (Maesa et al. 2020; Liu et al. 2020; Narayan & Tidström 2020; Mukherjee & Pradhan 2021; Mourtzis et al. 2023). DSCP enhances trust among supply chain participants, fostering better collaboration and transparent data sharing which are 'critical success factors' for BC to support CE (Kayikci et al. 2022). AI and the Metaverse, Jeon et al. (2022) find that 'In the Metaverse, the amount of data increases, the value increases, and the importance of reliability and security is increasing. BCT is required to guarantee the reliability of [this] data'.

Synchronised Transaction Process

BCT enables real-time, synchronised transactions, making sure all participants have the same, updated information (Lee et al. 2019, Leng et al. 2020; Kouhizadeh et al. 2022; Erol et al. 2022). In the CE context, this helps streamline material flows and reverse logistics, essential for effective recycling and reuse processes. Leng et al. (2020) write suggest tokens on BCs, which can represent a wide range of digital assets and can be transferred without any involvement of centralised entities or borders, could be studied to offer incentives to cooperate and compete to create CE ecosystems.

Cost Efficiency (supply chain)

BC streamlines and automates many supply chain processes, reducing overhead costs and minimising human error (Nandi et al. 2021; Upadhyay et al. 2021; Khan et al. 2022). This makes circular practices more financially viable, incentivising businesses to adopt CE principles in their supply chains. CE in product design is critical for EoL product management (Magrini et al. 2021).' Writing about BC, supply chain, and Industry 4.0, Javaid et al. (2021, p. 2) assert, '[BC]. avoids transactions intermediaries, potentially providing an efficient and cost-effective flow of goods and services.

3. Full Switch Theory and Information Cascade Theory

3.1 Full Switch Theory

In this section, we outline the methodology for conducting a thought experiment aimed at analysing the potential of BC to accelerate CE. The two theories driving the experiment are full switch and information cascade theory. Full switch theory asserts that to create a complete CE and reduce carbon emissions (and all GHGs), that a 'full switch' to renewables is necessary (Tàbara et al. 2018). As such, the methodology seeks to create an experiment in which a 'partial switch' and 'full switch' are made toward CE in BC 4.0 adoption. The partial switch consists of blockchain playing a supporting role to linear or polluting supply chains. A full switch would mean BC 4.0 implementation is done always to support circularity (Tàbara et al. 2018).

3.2 Information Cascade Theory

On the other hand, information cascade theory asserts that when a lack of reliable and accurate information is available that 'herd mentality' takes over. This leads to irrational behaviour whereby such game theory dilemmas as prisoner's dilemma and stage hunt come into play; without confidence of mutual benefit through cooperation (prisoner's dilemma) and without confidence that work spent on a mutual goal will result in greater rewards for all (stag hunt), then actors will perform selfishly. What this means for CE is that information cascades create risk toward a full switch to sustainability (Rich 2022).

3.3 Information Cascade Measurement

The measurement of information cascade consists of hype / performance. Two measurements are made for each measurement period which relate to 1. the trending on Google of a blockchain domain and 2. The performance of the blockchain domain (e.g. trading in the relevant stock, commodity, and / or (virtual) currency. If the two are correlated it would suggest that hype and performance could also be causally related. This would not be proved by the correlation itself but would require further investigation through a more rigorous experimental or longitudinal study in a future article. It is important to control other potential influencing factors, such as market conditions or technological advancements, in any subsequent studies. The eventual aim would be to isolate the effects of hype from these other variables to establish if, and to what extent, hype can indeed drive the performance of a blockchain domain.

4. Conceptual Framework

In the pursuit of understanding the transformational effect of Blockchain Technology (BCT) on the CE , our analysis proposes the following conceptual framework. This framework leverages the given equation to represent the dynamic interplay between the current state of CE, changes in production due to BCT-improved efficiency, efficiency variability per unit, CO_2 output per unit of product, and the influence of the information cascade.

- Dependent Variable: The performance of the Circular Economy (CE_perf) is what we are trying to model and predict with our equation.
- Independent Variables: Total CO2 output (TC), Change in production (ΔP), and CO2 output per unit of production (CU) are the variables we manipulate in our model to observe the effect on the dependent variable.
- Mediating Variables: Information Cascade of Blockchain (ICB) and Carbon output per unit (εU) are variables through which the independent variables exert their effects on the dependent variable.
- Control Variable: External variable (E), such as government regulation or yet unknown technological efficiency, is the control variable. It is the variable we try to keep the same in our model to ensure that the effects we observe are due to the variables we are manipulating (the independent variables) and not due to the control variable.

The proposed equation above provides an empirical model that encapsulates the complex interplay of different variables impacting the performance of a Circular Economy (CE_perf). This formula quantifies how total CO2 output (TC), changes in production (ΔP), CO_2 emissions per unit of product (εU), the information cascade of blockchain (ICB), and external factors (E) influence the circular economy's efficiency and sustainability.

TC, the total CO2 output, is placed in the numerator, indicating that as CO_2 emissions increase, the performance of the circular economy diminishes. However, this is counteracted by the denominator, which comprises a dynamic interaction between changes in production, the efficiency of the manufacturing process, and the information flow in blockchain technology. The expression (1 + ΔP * εU * (1 - ICB)) captures the transformative potential of blockchain technology, as it shows that increases in production and efficiency can mitigate the impact of CO_2 emissions, particularly if there is a strong information cascade effect in the blockchain (ICB).

Meanwhile, the addition of E, an external control variable, accounts for the influence of external factors such as policy regulations or other technological innovations that are not inherently part of the CE but can significantly impact its performance.

In sum, this formula serves as a holistic representation of the circular economy, capturing the multiplicity of factors at play. It allows us to model and predict CE performance based on several key variables and factors, thereby contributing significantly to our understanding of how to achieve a more efficient and sustainable circular economy. By understanding these relationships, we can better design and implement strategies that enhance the efficiency of the circular economy, further promoting sustainable development. The formula below encapsulates this concept in terms which allow for a simulation based on a best case / worst case thought experiment.

$$CE\_perf = TC / (1 + \Delta P * \varepsilon U * (1 - ICB)) + E$$

- CE_perf: Circular Economy performance is a measure of the efficiency and sustainability of the circular economy. A higher value signifies a more successful implementation of circular economy principles.
- TC: Total CO2 output represents the total amount of CO2 emitted due to production processes in a given time period. It's typically measured in Giga tonnes (Gt) of CO2.
- ΔP: Change in production is the percentage change in the amount of products manufactured over a given time period. An increase in production can potentially lead to higher CO2 emissions.

- εU: Carbon output per unit represents the average amount of CO_2 emitted per unit of product manufactured. It's a measure of the efficiency of the production process - a lower value signifies less CO_2 emitted per product and thus, a more efficient process.
- ICB: Information cascade of blockchain represents the amount of information flow in the blockchain, which can impact the circular economy performance. It's usually measured as a proportion (between 0 and 1) - a higher value suggests more effective information flow (1 - ICB).
- E: External (control) variable can represent various factors that are external to the circular economy process itself, such as government regulations or other technological innovations. It can have a significant impact on CE performance.

5. Scenario Analysis Method

This thought experiment seeks to provide a data-driven foundation for understanding the interplay between Blockchain Technology (BCT) and the advancement of a CE. Through a careful analysis of market trends, journal publications, and environmental data, it aims to elucidate the potential of BCT as a catalyst for sustainability.
Understanding the role of the information cascade (IC) enables a more accurate forecast of how companies and supply chains embrace economic and environmental performance. By considering the influence of IC, the modified formula recognises that higher IC levels may result in a more modular and fragmented adoption of BCT, prioritising economic benefits over environmental sustainability. This understanding helps in assessing potential risks, trade-offs, and impacts on sustainable practices within the context of BCT implementation. It provides insights into how companies may align or deviate from environmental performance goals based on their responses to IC dynamics.
The primary objectives of this thought experiment are:

Objective One:
To design and conduct a thought experiment that models 'full switch' (Best case) and ‘partial switch’ scenarios to a CE during the implementation of BCT 4.0 (Tàbara et al. 2018). This experiment will serve as a basis to explore and project the potential impact and viability of a full switch transition to renewables in the BCT 4.0 landscape as represented in data.

Objective Two:
To develop a methodology that evaluates the influence of IC, or the onset of 'herd mentality' due to lack of reliable information, on the 'green adoption' of BCT 4.0. This analysis will aim to quantify the potential risks and hindrances to sustainability caused by information gaps and the resulting irrational behaviors during the implementation of BCT 4.0.

Objective Three:
To incorporate a forecasting mechanism within the methodology that allows for the prediction of BCT 4.0's 'green adoption' rates under different scenarios. This would consider the results of the thought experiment, the influences of IC, and the implications of game theory dilemmas, to provide a comprehensive, future-oriented perspective on BCT 4.0's role in accelerating CE.

6. Data Collection

Data collection for this study is constructed around a multifaceted approach, drawing from both academic and industry-related insights to facilitate an inclusive simulation and subsequent analysis. However, it's crucial to highlight that the actual data utilised in the simulation is extrapolated and derived from the scope of the secondary literature and manipulated to fit the conceptual model for our investigation.

Our first step consists of gathering information from various blockchain-related publications available on established academic databases. This academic discourse provides comprehensive insights into the evolution, opportunities, and challenges of blockchain technology, establishing a rigorous theoretical base for our study.

In parallel, we draw upon extensive data related to environmental and sustainability metrics associated with blockchain technology and the Circular Economy. However, the specific figures used in our simulation are sample data, designed to mirror potential real-world scenarios based on the principles defined by the formula used in our analysis.

In addition to these sources, we collect information about the diffusion of information and its influence on blockchain adoption patterns from a diverse range of resources, including scholarly articles, industry reports, and surveys. Nonetheless, the Information Cascade of Blockchain (ICB) and the efficiency per unit (εU) values applied in our research are derived figures. They are intended to capture the trends and variability indicated by the literature rather than acting as direct measurements.

Table 4. BC economic and environmental performance: Best-case scenario (i.e. the Kuznet's curve)

Year	TC (%)	ΔP (%)	εU (%)	ICB (%)	E	CE_perf
2023	36.8	0	100	80	56	37.36
2024	35.9	2	99	78	48	38.27
2025	35.1	7	97	76	60	38.81
2026	34.2	12	94	74	43	39.91
2027	33.3	17	91	71	55	40.32
2028	32.5	22	88	68	49	41.33
2029	31.7	27	85	65	51	41.88
2030	30.8	32	81	62	57	42.92
2031	30	37	78	59	46	43.91
2032	29.2	42	74	56	53	44.76
2033	28.4	47	70	53	60	45.78
2034	27.6	52	66	50	45	46.83
2035	26.8	57	62	47	49	47.91
2036	26.1	62	58	44	56	48.99
2037	25.3	67	54	41	53	50.13

Source: author's calculations.

In this manner, our study leverages sample and simulation data, a strategy increasingly recognised as an effective tool for dealing with complex systems when direct measurement is challenging or impractical.

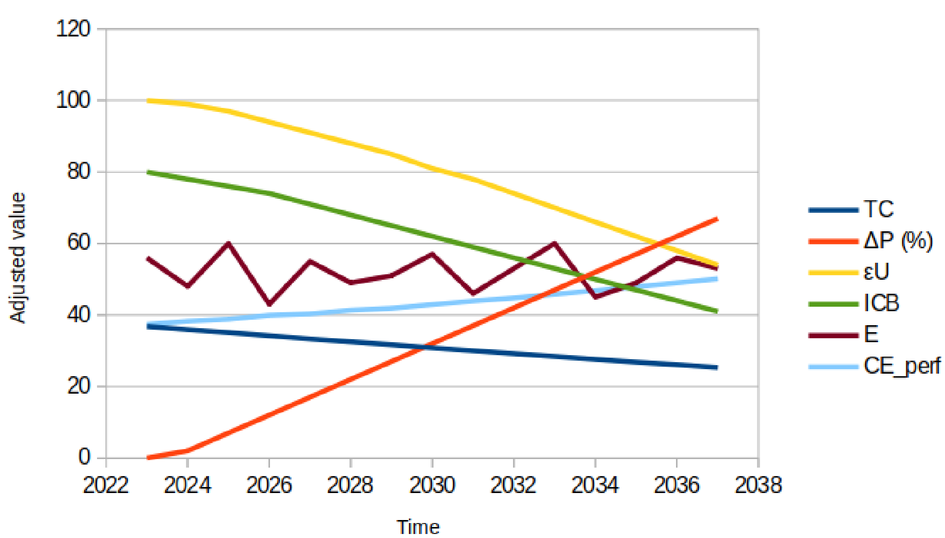

Figure 6. Best case scenario chart (adjusted values) (environmental Kuznets' curve).

Our primary goal is to conduct a simulation focusing on the potential correlation between the prevalence of blockchain-related academic publications and the 'green adoption' of Blockchain 4.0. The overarching objective is to understand how varying levels of information cascade might impact this adoption and apply game theory principles to predict behavioral responses amid the transition towards a sustainable Circular Economy.

Table 5. BC economic and environmental performance: Worst-case scenario (i.e. the Jevons paradox).

Year	TC (%)	ΔP (%)	εU (%)	ICB (%)	E	CE_perf
2023	36.8	0	100	80	56	37.36
2024	37	2	99	79	48	37.08
2025	37.3	7	99	78	60	36.69
2026	37.6	12	98	76	43	36.42
2027	37.9	17	97	75	55	36.06
2028	38.2	22	96	74	49	35.74
2029	38.5	27	95	73	51	35.36
2030	38.8	32	94	72	57	34.96
2031	39.1	37	92	70	46	34.63
2032	39.4	42	91	68	53	34.23
2033	39.7	47	90	67	60	33.82
2034	40	52	88	65	45	33.46
2035	40.3	57	86	63	49	33.08
2036	40.6	62	84	61	56	32.68
2037	40.9	67	82	59	53	32.32

Source: author's calculations.

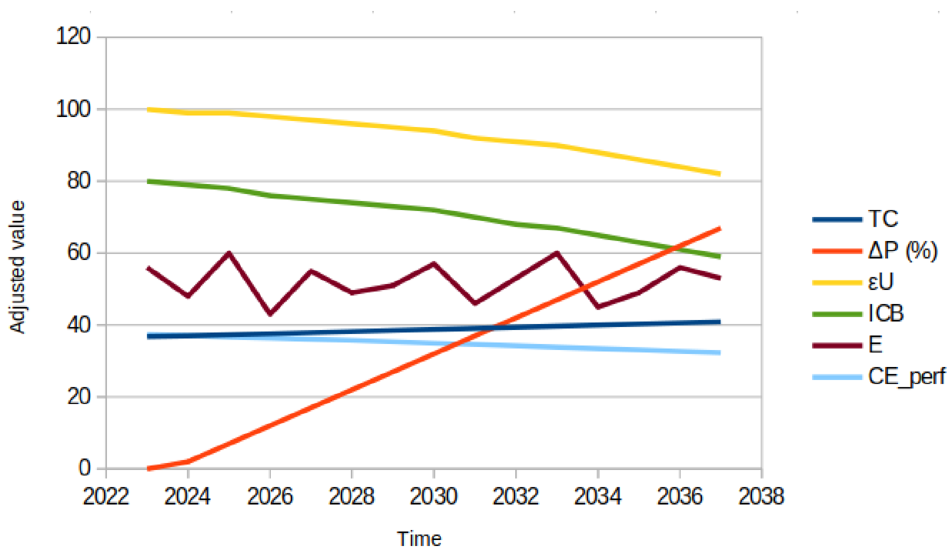

Figure 7. Worst case scenario chart (Jevons' paradox).

	Low Performance (less efficient)	**High Performance (more efficient)**
High Hype	High Risk Zone (Misallocated Resources, Possible Jevons Paradox)	Balanced Adoption Zone (Sustainable Growth, Low IC, High CE)
Low Hype	Low Impact Zone (Low Adoption, Low CE)	Optimal Adoption Zone (Controlled Growth, High CE, Lowest IC)

Figure 8. Information cascade matrix. Source: Own work.

The revised best-case and worst-case scenarios derived from the updated tables highlight the critical nature of efficiency improvements and the diffusion of accurate information in the adoption of Blockchain 4.0 (BC 4.0) for a Circular Economy (CE).

In the best-case scenario, significant improvements in efficiency (represented by a decrease in εU) are matched with an accelerated Information Cascade of Blockchain (ICB), reflecting a comprehensive understanding and successful application of the technology. As a result, the Total Carbon (TC) emissions are effectively controlled, even as production rates increase. This scenario suggests that with the right balance of technology use and understanding, the benefits of BC 4.0 can be fully harnessed to promote CE, thereby driving down carbon emissions and bolstering sustainability.

On the other hand, the worst-case scenario illustrates a situation where efficiency improvements are less significant, and the understanding and application of BC 4.0 technology (as represented by ICB) does not improve rapidly. This slower progress results in an increase in TC emissions over time, despite the fact that production levels are increasing. This scenario underscores that while improvements in technology efficiency can certainly help reduce carbon emissions, without a robust understanding and application (ICB), these improvements might not be enough to compensate for the increased production, leading to a negative impact on CE performance.

In conclusion, while technological efficiency is critical, it needs to be coupled with an accurate understanding and application (ICB) for the potential of BC 4.0 in promoting a Circular Economy to be fully realised. Without this balance, the overall performance may be undermined, leading to a scenario where despite efficiency improvements, the CE performance declines.

6.1 Analysis of the Simulation Results.

The simulation results under the best-case and worst-case scenarios underline the differing pathways that the impact of blockchain technology on the Circular Economy (CE) could follow, largely influenced by the varying levels of Information Cascade (IC).

In the best-case scenario, the Information Cascade of Blockchain (ICB) decreases more rapidly, indicating optimized usage and deeper comprehension of blockchain technology. This scenario mirrors a situation where accurate and comprehensive information about technology is widespread, triggering rational behavior and efficient use of blockchain. As a result, the efficiency per unit (εU) witnesses significant improvement, leading to a notable reduction in total carbon emissions (TC), even when production (ΔP) escalates. These dynamics emphasise the crucial role of technological efficiency in progressing the CE, further amplified by informed decision-making.

Conversely, in the worst-case scenario, the ICB descends more slowly, signifying a circumstance where limited or unreliable information could lead to sub-optimal use of blockchain technology. However, the inherent capacity of blockchain technology to enhance efficiency (εU) and reduce total carbon emissions (TC) remains evident, as indicated by the descending trend of CE performance (CE_perf) in spite of increasing efficiencies. External factors (E), such as regulatory changes and developments in non-blockchain technologies, also significantly affect the overall outcome.

6.2 Limitations and Future Research
While our simulation offers valuable insights into the potential trajectories of Blockchain 4.0 adoption in the context of the CE, it does have its limitations. One inherent limitation is the deterministic nature of the simulation. In reality, various factors influencing the adoption and impact of blockchain technology are highly stochastic, with external environmental variables potentially adding another layer of complexity. In other words, while the simulation is a robust tool to analyse possible outcomes, the real-world application might reveal more varied and unpredictable results due to unforeseen or uncontrollable factors.

Moreover, our study broadly considers Blockchain 4.0's adoption and does not delve into the impacts of specific applications of the technology. Future research could significantly extend this study by focusing on individual blockchain applications, studying their specific influences on the CE, and analyzing how different applications might interact with each other and with the wider socio-economic context.

6.3 Assessment of Blockchain's Potential in Closing the CE Loop
Our simulation illustrates the substantial potential of Blockchain 4.0 in driving the transition towards a Circular Economy (CE), even amidst varying degrees of information availability and efficiency.

Even in the worst-case scenario, where the Information Cascade of Blockchain (ICB) decreases at a slower pace, the merits of blockchain technology in boosting environmental efficiency are still evident, as shown in the declining trend of Circular Economy performance (CE_perf).

In contrast, the best-case scenario where the ICB declines more swiftly represents a scenario where the benefits and efficient utilisation of blockchain technology are thoroughly understood and implemented. This comprehension results in a notable rise in efficiency, leading to a more gradual increase in TC. Here, the significant role of blockchain in closing the CE loop is highlighted even further.

6.4 Blockchain's Potential in Mitigating Jevons Paradox
Jevons Paradox proposes that enhancements in efficiency might lead to heightened consumption rather than reductions. This paradox is particularly applicable in our worst-case scenario, where efficiency gains are accompanied by a rise in TC. Nonetheless, our simulations suggest that even under such conditions, Blockchain 4.0 can augment CE_perf, potentially disrupting the outcomes predicted by the Jevons Paradox.

6.5 Policy and Practical Implications
Our simulations underscore the importance of Blockchain 4.0 in promoting sustainable practices within the manufacturing industry and mitigating the potential impacts of Jevons Paradox. Policymakers should consider advocating for transparency and accurate information sharing, incentivising the adoption of Blockchain 4.0, and developing regulations to lessen the effects of the Jevons Paradox to avoid the previously mentioned tipping points which would accelerate global warming and climate change.

7. Conclusion
7.1 Summary of Findings
The study explores the complex interplay between Blockchain Technology (BCT) and its potential to augment CE. The findings emphasise that Blockchain, with its inherent attributes of transparency and traceability, can significantly enhance resource management and minimize waste in supply chains.

A notable observation was the dichotomy of outcomes that surfaced under different scenarios, reflecting the manifestation of either the Environmental Kuznets Curve or the Jevons Paradox.

7.2 Recommendations for Implementing Blockchain in the CE
To effectively integrate Blockchain 4.0 within the CE framework, a comprehensive strategy that encompasses policy, technology, and education is necessary. Policymakers can catalyse the adoption of Blockchain 4.0 by formulating appealing incentives and enforceable regulations.

7.3 Future Research Directions
Future research should delve deeper into the complex relationship between efficiency improvements, environmental impact, and the influences of Full Switch and Information Cascade theories, particularly in the context of

Blockchain 4.0 and CE. With a more profound understanding of these dynamics, we can optimise the application of blockchain technology to foster sustainable and efficient practices across various industries.

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Biography

Dr Chapman is an Assistant Professor of Project Management and APM Practitioner who conducts research and delivers lectures at the School of Strategy and Leadership (SSL) in the Faculty of Business and Law (FBL) at Coventry University (CU). Dr Chapman is also Director of the BA Business Management (Hons) course (CU). In Dr Chapman's vocational capacity, he delivers lectures and seminars to various academic modules at CU, as well as designs and delivers impact training for internal and external stakeholders, particularly in DSDM / Agile project management and ISO Risk management. Dr Chapman specialises in research-enhanced teaching, for example researching and developing his own Online Learning Environment (OLE) for simulation and dialogic feedback. Dr Chapman is also an ASPiRE fellow at FBL establishing an emerging portfolio of multi-modal academic outputs (including academic conferences) on the subjects of blockchain, sustainable production and consumption, narrative and decision-making simulation, and AI training. Dr Chapman is also an HEA Fellow.

Han Zhang (PhD candidate), currently serves as a Lecturer in Business Analytics at the School of Strategy and Leadership. She has been instrumental in several teaching capacities, the most recent of which saw her spearheading the module on Data Mining Methodologies and Applications for postgraduate students. Within this role, she skillfully employed IBM SPSS software to teach students about data mining, enabling them to analyse survey data and text data efficiently. In addition to her teaching responsibilities, Han demonstrates a strong commitment to student mentorship, overseeing eleven undergraduate students in their individual projects. She also lends her expertise to the SIGMA Centre at Coventry University, providing supportive guidance to students. At present, Han is immersing herself in her Doctoral studies, specializing in Supply Chain Management. Her research centers on the integration of advanced technologies within a manufacturing context, exploring areas such as operations management, blockchain, Industry 4.0, Circular Economy (CE), and supply chain management. Her work aims to elucidate the transformative potential of these technologies on the industry.