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SUSTAINABLE BLOCKCHAIN TECHNOLOGIES

AN ASSESSMENT OF SOCIAL AND ENVIRONMENTAL IMPACTS OF BLOCKCHAIN-BASED TECHNOLOGIES

BY
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DISSERTATION SUBMITTED 2021

AALBORG UNIVERSITY
DENMARK

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AN ASSESSMENT OF SOCIAL AND ENVIRONMENTAL IMPACTS OF BLOCKCHAIN-BASED TECHNOLOGIES

by

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Dissertation submitted

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Susanne Köhler earned a B.Sc. in Environmental and Resource Management in 2014 from Brandenburg University of Technology in Cottbus, Germany, during which she spent one semester at National Cheng Kung University in Taiwan. Afterwards, she worked at ESC-BORDA Cambodia in Phnom Penh, Cambodia supporting the implementation of School Based Sanitation Projects in rural and peri-urban schools around Cambodia.

In 2018, Susanne completed her M.Sc. degree in Sustainability, Society and the Environment at Kiel University, Germany, during which she spent one semester at Université de Nantes in France. She also completed an internship at adelphi research in Munich supporting the SEED global partnership for action on sustainable development and the green economy. While writing her master thesis, Susanne worked at brands & values GmbH in life cycle assessment and sustainability consulting.

From August 2018 to July 2021 Susanne was enrolled as a PhD fellow at the Department of Planning at Aalborg University, Denmark, during which she worked on the Sustainable Blockchain Technologies Project. Due to the COVID-19 pandemic her collaborations took place online with Prof. Joseph Sarkis from Worcester Polytechnic Institute, MA, USA, and Simon Bager, UC Louvain, Belgium. Next to her research, Susanne volunteers at PositiveBlockchain.io where she engages in various activities ranging from moderating panels, mentoring at hackathons, and supporting collaboration projects.

ENGLISH SUMMARY

Over the past years, a hype has emerged around blockchain technology and cryptocurrencies. Within that hype, blockchain technology is depicted in contrasting lights. While Bitcoin and other cryptocurrencies are claimed to have significant environmental footprints, blockchain applications are expected to create positive impacts on various industries. Blockchain technology and its applications are still in early stages of development, and it is unclear which applications will be adopted and what their impact will be.

This PhD project is developed within the theoretical framework of prospective technology assessment to investigate the trade-offs stemming from the adoption of blockchain technology. There is an urgent need for solid scientific research estimating the impacts of blockchain applications due to the fast expansion of the technology and to anticipate potential unwanted environmental and social impacts. Therefore, this PhD project scientifically investigated the environmental and social impacts blockchain technology will have.

In order to address this broad objective, two sub-objectives were defined: 1) estimate the environmental impact of blockchain technology itself using the example of Bitcoin; and 2) investigate how blockchain-based technologies foster sustainability using the example of applications in supply chains. According to previous studies Bitcoin mining consumed at least 1 TWh in 2014 and is projected to consume 184 TWh in 2021. The associated carbon footprint was estimated to be 3-13 $MtCO_2$ from 2016 to mid-2018, with a projected 90 $MtCO_2$ in 2021. Existing studies do not take a life cycle perspective, as only the impacts of electricity consumption are considered. These studies further use ad hoc approaches for calculating environmental footprints and do not build on established frameworks. Additionally, sensitivity and uncertainty analyses are lacking. This PhD project produced the first reproducible life cycle assessment of Bitcoin mining that includes different phases within the life cycle, identified environmental hotspots, and conducted sensitivity and uncertainty analyses. The project also highlighted the nonlinearity of upscaling Bitcoin mining as an emerging technology and discussed the limitations of LCA models for long-term projections of such a volatile and uncertain system.

Applications of blockchain technology in supply chains provide potentials in extending visibility and traceability, supporting supply chain digitalization and disintermediation, providing improved data security for data sharing, and incorporating smart capabilities. However, research in this field does not incorporate real experiences, and there is little focus on how these potentials can be fulfilled. Moreover, there is an absence of research relating blockchain-based technologies to existing solutions. To address these gaps, this PhD project investigated real cases demonstrating how blockchain-based technologies are implemented in supply chains, how positive social and environmental impacts can be created, and how blockchain-based technologies interact with existing solutions.

The PhD project adopted a mixed-methods approach to assess different blockchain implementations. Life cycle assessment has been acknowledged as a valuable tool to support the identification of environmental improvement potentials in early development stages. Thus, to address the first objective, life cycle assessment was applied as a quantitative approach for environmental assessment. Qualitative research can also be suitable for prospective technology assessment, as it is conducted when a phenomenon needs to be explored, yet data is scarce or cannot be easily measured. As blockchain technologies are still an emerging technology, with little data available, qualitative research can be used to explore specific cases and experiences. Two case study-based analyses and one grounded theory-based study using interviews with stakeholders were conducted.

The results of this PhD project show that the energy consumption and carbon footprint of Bitcoin mining have continuously increased over the past years, reaching 72 TWh and 60.7 $MtCO_2$ for the first six months of 2021. Coal-powered regions particularly contribute to the carbon footprint, while hydro-rich regions add little. Across the life cycle, the use phase is the major contributor, accounting for over 99% of the impacts. The main driving parameters are the hashrate, the energy efficiency of the equipment, and the mining locations. The PhD project further indicated that the impact per TH mined decreases. However, the hashrate grows at a faster rate than the impacts decrease. While life cycle assessment has proven a valuable tool to provide a more holistic, solid, and scientific assessment of the environmental impacts of Bitcoin

mining, it is also limited in its ability to reflect and address the high fluctuations and uncertainties of Bitcoin mining.

The findings of the PhD project further illustrate that blockchain technology is not a stand-alone technology but rather part of a system of technologies. Therefore, it may not be possible to distinguish between the impacts of using blockchain technology and the entire system of technologies. Blockchain-based technologies vary considerably in their design. Depending on the design, blockchain-based technologies can have different relationships with existing alternatives. Blockchain-based technologies can co-exist, generate synergies, or compete with existing solutions. The PhD project additionally generated a middle-range theory of how blockchain-based technologies in supply chains can create positive social and environmental impacts in supply chains, illustrating this in four specific impact pathways. These results, which show several ways in which blockchain-based technologies can be employed to create positive impacts, serve as a starting point for understanding the different ways blockchain technology can be applied in supply chains and beyond.

This PhD project illuminates the supposed contradiction of blockchain technology – blockchain technology in the form of mining will be detrimental for the planet, while blockchain applications can save it. This supposed contradiction is, however, conditional. It only exists when proof-of-work blockchains that require mining are used. If, instead, a non-proof-of-work blockchain is used for blockchain-based technologies that foster sustainability, this contradiction does not exist. While proof-of-work blockchains have high carbon footprints and energy consumption levels, blockchain-based technologies can be a tool to address sustainability as part of a system of technologies. However, system design significantly affects the creation of positive social and environmental impacts. Many actors, including technology companies, brands, governments, users, researchers, and society, are involved in shaping the development of blockchain technology. As such, it lies in the hands of many to influence the development of this emerging technology.

DANSK RESUME

I løbet af de seneste år har både blockchain-teknologi og kryptovalutaer fået øget opmærksomhed. Især blockchain-teknologi bliver set i kontrasterende lys. Mens Bitcoin og andre kryptovalutaer hævdes at have betydelige miljømæssige fodspor, forventes anvendelsen af blockchain at skabe positive virkninger på forskellige brancher. Det er dog usikkert, hvor hurtig og omfattende denne ændring vil være. Blockchain-teknologien og dens anvendelse er stadig i de tidlige stadier af udviklingen, og det er stadig uklart, hvilke anvendelser, der vil blive vedtaget, og ligeledes hvad deres indvirkning vil være.

Dette ph.d.-projekt er udviklet inden for den teoretiske ramme for potentiel teknologivurdering for at undersøge kompromiser, der stammer fra vedtagelsen af blockchain-teknologi. Der er et presserende behov for solid videnskabelig forskning, der estimerer virkningerne af blockchain-applikationer på grund af den hurtige udvidelse af teknologien og forudse potentielle uønskede miljømæssige og sociale påvirkninger. Derfor undersøgte dette ph.d.-projekt på videnskabelig vis de miljømæssige og sociale virkninger, blockchain-teknologien vil have.

For at imødekomme dette brede mål blev to delmål defineret: 1) estimer miljøpåvirkningen af selve blockchain-teknologien ved hjælp af Bitcoin; og 2) undersøg, hvordan blockchain-baserede teknologier fremmer bæredygtighed ved anvendelse i forsyningskæder. Ifølge tidligere undersøgelser forbrugte Bitcoin-minedrift mindst 1 TWh i 2014 og forventes at forbruge 184 TWh i 2021. Det tilknyttede CO_2-fodaftryk blev estimeret til at være 3-13 $MtCO_2$ fra 2016 til midten af 2018 med en forventet 90 $MtCO_2$ i 2021. Eksisterende undersøgelser anvender ikke et livscyklusperspektiv, da kun påvirkning af elforbruget tages i betragtning. Disse undersøgelser anvender yderligere ad hoc-fremgangsmåder til beregning af miljømæssige fodspor og bygger ikke på etablerede rammer. Derudover mangler følsomheds- og usikkerhedsanalyser. Dette ph.d.-projekt producerede den første reproducerbare livscyklusvurdering af Bitcoin-minedrift, der inkluderer forskellige faser inden for livscyklussen, identificerede miljømæssige hotspots og gennemførte følsomheds- og usikkerhedsanalyser. Projektet fremhævede også den ikke-lineære opskalering af Bitcoin-minedrift som en ny teknologi og drøftede begrænsningerne ved LCA-modeller til langsigtede fremskrivninger af et sådant ustabilt og usikkert system.

Anvendelse af blockchain-teknologi i forsyningskæder kan eventuelt forøge både synlighed og sporbarhed, understøtte digitalisering og forsyning af forsyningskæden, give forbedret datasikkerhed til datadeling og inkorporere smarte funktioner. Dog mangler der konkrete erfaringer inden for dette forskningsområde, og der er begrænset fokus på, hvordan disse potentialer kan udnyttes. Der er desuden mangel på forskning, der relaterer blockchain-baserede teknologier til eksisterende løsninger. Derfor undersøgte dette ph.d.-projekt reelle sager, der demonstrerede, hvordan blockchain-baserede teknologier implementeres i forsyningskæder, hvordan positive sociale og miljømæssige påvirkninger kan skabes, og hvordan blockchain-baserede teknologier interagerer med eksisterende løsninger.

Ph.d.-projektet vedtog en blandet metode tilgang til at vurdere forskellige blockchain implementeringer. Livscyklusvurdering er blevet anerkendt som et værdifuldt redskab til at understøtte identificeringen af miljøforbedringspotentialer i tidlige udviklingsfaser. For at imødegå det første mål blev livscyklusvurdering således anvendt som en kvantitativ tilgang til miljøvurdering. Kvalitativ forskning kan også være velegnet til fremtidig teknologivurdering, da den udføres, når et fænomen skal undersøges, men data er enten mangelfulde eller ikke let målbare. Da blockchain-teknologier stadig er en ny teknologi, med få tilgængelige data, kan kvalitativ forskning bruges til at udforske specifikke tilfælde og oplevelser. Ph.d.-projektet består dermed af to casestudiebaserede analyser og en grundliggende teoribaseret undersøgelse ved hjælp af interviews med interessenter.

Resultaterne af dette ph.d.-projekt viser, at energiforbrug og kulstofaftryk ved Bitcoin-minedrift kontinuerligt er steget i de sidste år og nåede 72 TWh og 60,7 MtCO2 i de første seks måneder af 2021. Kuldrevne regioner bidrager især til øget kulstofaftryk, mens vandrige regioner tilføjer mindre. På tværs af livscyklussen er brugsfasen den største bidragyder og tegner sig for over 99% af påvirkningerne. De vigtigste køreparametre er hashrate, udstyrets energieffektivitet og minedrift. Ph.d.-projektet viste endvidere, at virkningen pr. TH minet faldt. Dog vokser hashratet hurtigere, end virkningerne falder. Mens livscyklusvurdering har vist sig at være et værdifuldt værktøj til at give en mere holistisk, solid og videnskabelig vurdering af miljøbelastningen af Bitcoin-minedrift, er den også begrænset i dens evne til at reflektere og imødegå de høje udsving og usikkerheder af Bitcoin minedrift.

Resultaterne af ph.d.-projektet illustrerer yderligere, at blockchain-teknologi ikke er en enkeltstående teknologi, men snarere en del af et system af teknologier. Derfor er det måske ikke muligt at skelne mellem virkningerne af at bruge blockchain-teknologi og hele teknologisystemet. Blockchain-baserede teknologier varierer betydeligt i deres design. Afhængigt af designet kan blockchain-baserede teknologier have forskellige forhold til eksisterende alternativer. Blockchain-baserede teknologier kan eksistere side om side, generere synergier eller konkurrere med eksisterende løsninger. Ph.d.-projektet genererede desuden en mellemklasse-teori om, hvordan blockchain-baserede teknologier i forsyningskæder kan skabe positive sociale og miljømæssige påvirkninger i forsyningskæderne, hvilket er illustrerer ved fire specifikke virkningsveje. Disse resultater, der viser flere måder, hvorpå blockchain-baserede teknologier kan anvendes til at skabe positive virkninger, tjener som udgangspunkt for at forstå de forskellige måder, blockchain-teknologi kan anvendes i forsyningskæder.

Dette ph.d.-projekt belyser den formodede modsigelse af blockchain-teknologi – blockchain-teknologi i form af minedrift vil være skadelig for planeten, mens anvendelsen af blockchain samtidig kan redde den. Denne formodede modsigelse er dog betinget. Den eksisterer kun, når der anvendes proof-of-work-blockchains, der kræver minedrift. Hvis der i stedet anvendes en non-proof-of-work-blockchain til blockchain-baserede teknologier, der fremmer bæredygtighed, eksisterer denne modsigelse ikke. Mens proof-of-work-blockchains har høje CO2-fodspor og energiforbrugsniveauer, kan blockchain-baserede teknologier være et redskab til at tackle bæredygtighed som en del af et teknologisystem. Systemdesign kan dog væsentligt påvirke skabelsen af positive sociale og miljømæssige påvirkninger. Mange aktører, herunder teknologivirksomheder, mærker, regeringer, brugere, forskere og samfund, er involveret i at forme udviklingen af blockchain-teknologi. Som sådan ligger det i hænderne på mange at påvirke udviklingen af denne nye teknologi.

DEUTSCHE ZUSAMMENFASSUNG

In den letzten Jahren ist ein Hype um Blockchain-Technologie und Kryptowährungen entstanden. Dabei wird Blockchain-Technologie gegensätzlich dargestellt. Während Bitcoin und andere Kryptowährungen erhebliche ökologische Fußabdrücke haben sollen, werden Blockchain-Anwendungen zahlreiche positive Auswirkungen nachgesagt. Blockchain-Technologien und ihre Anwendungen befinden sich jedoch noch in frühen Entwicklungsstadien und es ist unklar, welche Anwendungen sich durchsetzen werden und welche Auswirkungen sie haben werden.

Die prospektive Technologiebewertung gibt den theoretischen Rahmen für dieses PhD-Projekt. Aufgrund der schnellen Ausbreitung der Technologie besteht dringender Bedarf an solider wissenschaftlicher Forschung, um die Auswirkungen von Blockchain-Technologien und ihren Anwendungen abzuschätzen und potenzielle unerwünschte Umwelt- und soziale Auswirkungen zu antizipieren. Daher untersuchte dieses PhD-Projekt die ökologischen und sozialen Auswirkungen der Blockchain-Technologie.

Um diesem weit gefassten Ziel gerecht zu werden, wurden zwei Teilziele definiert: 1) Abschätzung der Umweltauswirkungen der Blockchain-Technologie am Beispiel von Bitcoin; und 2) Untersuchung von Mechanismen wie Blockchain-Anwendungen Nachhaltigkeit fördern am Beispiel von Anwendungen in Lieferketten. Laut früheren Studien verbrauchte Bitcoin Mining 2014 mindestens 1 TWh und wird voraussichtlich 184 TWh im Jahr 2021 verbrauchen. Der damit verbundene CO_2-Fußabdruck wurde von 2016 bis Mitte 2018 auf 3-13 $MtCO_2$ geschätzt. Für 2021 werden 90 $MtCO_2$ prognostiziert. Bestehende Studien betrachten nicht den kompletten Lebenszyklus von Bitcoin Mining. Sie analysieren nur die Auswirkungen des Stromverbrauchs. Diese Studien verwenden weiterhin Ad-hoc-Ansätze zur Berechnung von Umweltfußabdrücken und bauen nicht auf etablierten Methoden auf. Zudem fehlen Sensitivitäts- und Unsicherheitsanalysen. Das PhD-Projekt erstellte die erste reproduzierbare Ökobilanz von Bitcoin Mining, die verschiedene Phasen innerhalb des Lebenszyklus umfasst, Umwelt-Hotspots identifiziert und Sensitivitäts- und Unsicherheitsanalysen durchgeführt

hat. Das Projekt hob außerdem hervor, dass das Wachstum von Bitcoin Mining nicht linear verläuft und diskutierte die Grenzen von Ökobilanzmodellen für langfristige Projektionen eines so volatilen und unsicheren Systems.

Anwendungen der Blockchain-Technologie in Lieferketten bieten Potenziale für verbessertes Vertrauen, bessere Sichtbarkeit und Rückverfolgbarkeit, zur Unterstützung von Digitalisierung, zur Verbesserung der Datensicherheit und zur Integration smarter Funktionen. Allerdings mangelt es an Forschung, die auf Erfahrungen mit Blockchain-Technologien basiert, und es wird nicht beschrieben *wie* die erläuterten Potenziale ausgeschöpft werden können. Darüber hinaus fehlt es an Forschung, die Blockchain-Anwendungen mit bestehenden Lösungen vergleicht. Um diese Forschungslücken zu schließen, untersuchte das PhD-Projekt reale Fälle, die zeigen, wie Blockchain-Anwendungen in Lieferketten implementiert werden, wie positive soziale und ökologische Auswirkungen erzeugt werden können und wie Blockchain-Anwendungen mit bestehenden Lösungen interagieren.

In dem PhD-Projekt wurden sowohl quantitative als auch qualitative Forschungsmethoden verwendet. Ökobilanz wurde als wertvolles Instrument zur Identifizierung von Umweltverbesserungspotenzialen in frühen Entwicklungsstadien anerkannt. Um das erste Teilziel zu erreichen, wurde daher Ökobilanz als quantitativer Ansatz für die Umweltbewertung verwendet. Qualitative Forschung kann auch für die prospektive Technologiebewertung geeignet sein, da sie durchgeführt wird, wenn ein Phänomen erforscht werden muss, es aber an Daten mangelt oder diese nicht einfach gemessen werden können. Da Blockchain-Technologie immer noch eine neue Technologie mit wenigen verfügbaren Daten ist, kann qualitative Forschung verwendet werden, um spezifische Fälle und Erfahrungen zu untersuchen. Es wurden zwei Fallstudien und eine „Grounded Theory“ Studie basierend auf Stakeholder-Interviews durchgeführt.

Die Ergebnisse dieses PhD-Projekts zeigen, dass der Energieverbrauch und der CO_2-Fußabdruck von Bitcoin Mining in den letzten Jahren kontinuierlich gestiegen sind und in den ersten sechs Monaten von 2021 72 TWh und 60,7 Mt CO_2 erreicht haben. Besonders Regionen mit viel Energie aus Kohle tragen zum CO_2-Fußabdruck bei, während der Anteil am CO_2-Fußabdruck für Regionen mit viel Wasserkraft gering ist. Über den gesamten Lebenszyklus hinweg trägt die Nutzphase mit über 99% am meisten dazu bei. Die wichtigsten treibenden Parameter sind die Hashrate, die Energieeffizienz der Mining-Maschinen und die Mining-Standorte. Das PhD-Projekt zeigte außerdem, dass die Auswirkungen pro TH weniger werden, während die Hashrate allerdings schneller ansteigt, als die Auswirkungen pro TH abnehmen. Obwohl sich Ökobilanz als ein wertvolles Instrument erwiesen hat, um eine ganzheitlichere, solidere und wissenschaftlichere Bewertung der Umweltauswirkungen von Bitcoin Mining zu ermöglichen, ist die Methode begrenzt darin, die hohen Schwankungen und Unsicherheiten von Bitcoin Mining abzubilden.

Die Ergebnisse des PhD-Projekts verdeutlichen weiter, dass die Blockchain-Technologie keine alleinstehende Technologie ist, sondern Teil eines Systems von Technologien. Daher ist es gegebenenfalls nicht möglich, zwischen den Auswirkungen, die auf Blockchain-Technologien zurückzuführen sind und denen des gesamten Technologiesystems zu unterscheiden. Blockchain-Anwendungen unterscheiden sich erheblich in ihrem Design. Sie können je nach Design unterschiedliche Beziehungen zu bestehenden Alternativen aufweisen. Blockchain-Anwendungen können neben Alternativen existieren, Synergien mit ihnen generieren oder mit bestehenden Lösungen konkurrieren. Das PhD-Projekt brachte des Weiteren eine „Middle-range Theory“ hervor, die beschreibt wie Blockchain-Anwendungen in Lieferketten positive soziale und ökologische Auswirkungen erzeugen können, und veranschaulicht dies in vier spezifischen Wirkungspfaden. Diese Ergebnisse, die mehrere Möglichkeiten aufzeigen, wie Blockchain-Anwendungen eingesetzt werden können, um positive Auswirkungen zu erzielen, dienen als Ausgangspunkt für ein besseres Verständnis von verschiedenen Anwendungsmöglichkeiten der Blockchain-Technologie in Lieferketten und darüber hinaus.

Dieses PhD-Projekt beleuchtet den vermeintlichen Widerspruch von Blockchain-Technologien – Blockchain-Technologie wird einerseits den Planeten durch Mining zerstören, während Blockchain-Anwendungen ihn andererseits retten können. Dieser vermeintliche Widerspruch ist jedoch nur bedingt wahr. Er existiert nur, wenn Proof-of-Work-Blockchains, welche Mining erfordern, verwendet werden.

Wird stattdessen eine Blockchain mit anderem „Consensus Mechanismus“ verwendet, die dazu entwickelt wurde Nachhaltigkeit zu fördern, besteht dieser Widerspruch nicht. Während Proof-of-Work-Blockchains einen hohen CO_2-Fußabdruck und einen hohen Energieverbrauch aufweisen, können Blockchain-Anwendungen ein Instrument sein, um Nachhaltigkeit als Teil eines Technologiesystems zu fördern. Das Systemdesign hat jedoch einen erheblichen Einfluss darauf, welche positiven soziale und ökologische Auswirkungen es geben wird. Viele Akteure, darunter Technologieunternehmen, Firmen, Regierungen, Nutzer, Forscher und die Gesellschaft, sind an der Entwicklung der Blockchain-Technologie beteiligt. Daher liegt es in der Hand vieler, die Entwicklung dieser neuen Technologie zu beeinflussen.

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Aalborg, July 2021

Susanne Köhler

LIST OF ACADEMIC PUBLICATIONS

The following publications have been completed as part of this PhD dissertation:

I. Köhler S., Pizzol M. 2019. **Published**. „Life Cycle Assessment of Bitcoin Mining". In *Environmental Science and Technology*, 53, 13598–13606.
II. Köhler S., Pizzol M. 2020. **Published**. "Technology Assessment of Blockchain-based Technologies in Supply Chains". In *Journal of Cleaner Production*, 269, 122193.
III. Pizzol M., Sacchi R., Köhler S., Erjavec A. A. 2021. **Published**. "Non-linearity in the Life Cycle Assessment of Scalable and Emerging Technologies". In *Frontiers in Sustainability*, 1, 611593.
IV. Köhler S., Pizzol M., Sarkis J. 202X. **In Review**. "Unfinished Road – Blockchain to Sustainability in Supply Chains". In *Frontiers in Blockchain*.
V. Köhler S., Bager S., Pizzol M. 202X. **Submitted**. "Sustainability standards and blockchain in agro-food supply chains: Synergies and conflicts". In *Technological Forecasting and Social Change.*

CONTRIBUTION TO ACADEMIC PUBLICATIONS

I. Main author. Main contributor to the modeling of Bitcoin mining, results calculation, and interpretation.
II. Main author. Main contributor to data collection, technology analysis, and interpretation.
III. Third author. Main contributor to the modeling of Bitcoin mining, calculation of results for the Bitcoin mining model, and interpretation of these results.
IV. Main author. Main contributor to conducting interviews, data analysis, and interpretation.
V. Main author. Main contributor to data collection, data analysis, and interpretation.

DISSEMINATION

A full overview of the dissemination activities can be found here: https://vbn.aau.dk/en/persons/144007/activities/

Conference presentations and panel participations:

- Presentation “Blockchain-based Technologies in the Food Supply Chain – A Comparative Analysis” at Transforming for Sustainability Conference, 28 November 2018, Copenhagen, Denmark
- Presentation “The Carbon Footprint of Bitcoin – Are we moving towards a sustainable blockchain future?” at the 9th International Conference on Life Cycle Management, September 2, 2019, Poznan, Poland
- Poster Presentation “Blockchain-based Technologies in the Food Supply Chain – A Comparative Assessment” at LCA Food 2020, October 2020, Online
- “Fashion Tech Summit: NFTs and Sustainability” panel speaker, event organized by DressX, 4 June 2021, Online
- “Sustainability in blockchain” panel speaker, event organized by Blockrocket, 16 June 2021, Online

Selection of media coverage and expert requests:

- Interview about Article I *“Bitcoin's climate change impact may be much smaller than we thought”* in New Scientist, 20 November 2019
- Interview about Article I *“Bitcoin's Carbon Footprint May Not Be As Massive As Previously Estimated”* in Gizmodo, 20 November 2019
- Interview about my research and Article IV *“Q&A: Susanne Köhler explores how blockchain can create social and environmental impacts”* in CGIAR, 17 June 2020
- Expert request for *“Tesla’s $1.5 billion bitcoin purchase clashes with its environmental aspirations”* in The Verge, 9 February 2021
- Expert request for *“Can cryptocurrency be climate conscious?”* (Part 1) & *“Can cryptocurrencies help the planet?”* (Part 2) in the Global Landscapes Forum, 22 & 23 March 2021
- Expert request for *“NFTs Are Shaking Up the Art World. They May Be Warming the Planet, Too.”* In The New York Times, 13 April 2021
- Expert request for *“In Coinbase’s Rise, a Reminder: Cryptocurrencies Use Lots of Energy”* in The New York Times, 14 April 2021
- Expert request *“All that mined is not green: Bitcoin’s carbon footprint hard to estimate*” in Cointelegraph, 10 April 2021
- Interview on the Physics World Weekly podcast, 22 April 2021

Academic Comment:

- Köhler & Pizzol (2021) *“Bitcoin: Energy intensive by design”*. In Digitizing a sustainable future. One Earth 4:768–771. doi: 10.1016/j.oneear.2021.05.012

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1. INTRODUCTION: BLOCKCHAIN TECHNOLOGY WILL SAVE THE WORLD

This section introduces the reader to the context that surrounds blockchain technologies and their potential role in both hindering and facilitating sustainability in the future (Section 1.1). The scope and the main purpose of this PhD thesis is then presented (Section 1.2). The section ends with a description of the structure of this PhD thesis (Section 1.3).

1.1. CONTEXT

Blockchain technology was first introduced in 2008 as part of the Bitcoin whitepaper by an unknown person or group named Satoshi Nakamoto, which mainly integrated existing ideas into one protocol (Nakamoto 2008). In the whitepaper, Nakamoto (2008) proposed a system for electronic transactions allowing users to send payments directly from one party to another without going through financial institutions, thereby eliminating the need for a trusted third party. The Bitcoin protocol, built on blockchain technology, solves the issue of double-spending that previous electronic money systems were struggling with and proposes a system based on a peer-to-peer network that records the public history of transactions and is virtually immutable (Nakamoto 2008). The Bitcoin whitepaper was first published in the middle of the most significant and widest-ranging economic recessions since the 1930s. While it may not have been developed as a response to the financial downturn, the timing provided fruitful grounds for such an idea to take off and may have accelerated the spread outside cypherpunk and crypto-anarchist-inspired subcultures in which it originated (Swartz 2018). Bitcoin has since grown to be the largest cryptocurrency by market capitalization (about 660 million USD as of June 2021; Blockchain.com 2021a) and has inspired innumerable applications that use the underlying blockchain technology.

Within the past years, a hype has developed around blockchain technology. Bitcoin, as well as other cryptocurrencies, have broken price record after price record, and increasing numbers of users have bought various tokens. Bitcoin surpassed a market price of USD 60,000 in April 2021 before falling again to USD 35,000 in June (Blockchain.com 2021b). Google Trends shows a significant interest in blockchain technology during times of high market prices, especially in cryptocurrencies such as Bitcoin and Ethereum (Google 2021). However, concerns are continuously raised about the sustainability of Bitcoin under the rationale that since the Bitcoin network uses significant energy to run its mining operations, its environmental impact could be substantial. Popular media has even claimed that Bitcoin might be on track to use all the world's energy by 2020 (Cuthbertson 2017), be solely responsible for failure to reach the Paris Agreement (Gabbatiss 2018), and consume almost 10 times more energy than Google, Microsoft, and Facebook combined (Deacon 2021). Microsoft founder Bill Gates recently said, "Bitcoin uses more electricity per transaction than any other method known to mankind" (Deacon 2021). Elon Musk sent the cryptocurrency market tumbling after tweeting that Tesla would no longer accept vehicle purchases in Bitcoin due to concerns about fossil fuel use in Bitcoin mining (Musk 2021). A controversial academic article suggested that Bitcoin alone could be responsible for surpassing 2°C of warming within a few years (Mora et al. 2018). Less controversial literature estimated that the energy consumption of Bitcoin mining is higher than that of Austria and that Bitcoin already consumes more electricity than half of the world's data centers (de Vries 2021).

At the same time, however, many technology experts and visionaries have described blockchain technology, the underlying technology of Bitcoin, as a disruptive, game-changing, and ground-breaking technology that is likely to radically change the world we live in for the better (Wile 2014). Blockchain technology is even claimed to become a more democratic and sustainable alternative to several current technologies (The Economist 2016). It is argued that blockchain technology holds tremendous potential for sustainable development through its application in various fields. Organizations such as the UN (UN 2017) and the OECD (Berryhill et al. 2018) as well as companies and political entities are exploring the use of blockchain technology for different purposes. In supply chain management, blockchain technology can be used to create transparent and accountable mechanisms that track and certify the origins of products and raw materials, e.g. tracking diamonds to avoid “blood diamonds” (Caffyn 2015) and tracking line-caught tuna (Provenance 2016) or other food products (Noel 2017) from source to shop. With respect to energy management, blockchain technology seems to have a great potential as well. The Brooklyn-based start-up LO3 Energy is developing a concept for the local generation and storage of energy, changing how electricity is sold and used (LO3 Energy 2018). Other energy-related applications of blockchain technology aim at monitoring greenhouse gas inventories for use in carbon credits, improving emissions trading, facilitating clean energy trading, and enhancing climate financing (UNFCCC 2017). These are just a few promising applications that could foster sustainability.

1.2. AIMS AND OBJECTIVES

Blockchain technology is depicted in contrasting lights. Bitcoin and other blockchains are claimed to have significant environmental footprints, while blockchain applications promise positive change in various industries. However, it is unclear how rapid or extensive this change will be. As with most emerging technologies is the case, the future is uncertain, even if a technology is considered to have the potential to disrupt many industries. Blockchain technology and its applications are still in their infancy. These applications need time to develop, and it is unclear which of them will be adopted by the market and what their real-life impact will be.

There is a lack of information on the actual environmental footprint of blockchain technology itself, how the implementations of blockchain-based technology work, and whether they will lead to positive change. Developed within the theoretical framework of *prospective technology assessment*, the project investigates the trade-offs arising from the adoption of blockchain technology. While blockchain technology allows for secure, robust, and trustworthy solutions and can create clear improvements compared to current technologies in terms of traceability and transparency, these benefits come at a cost. The key issue is thus determining the magnitude of these effects and how they will affect society and the environment.

Solid scientific studies estimating the effects of expected blockchain applications are currently lacking and, due to the rapid widespread of the technology, are urgently needed in order to anticipate potential unwanted environmental and social consequences. Thus, this project aims at investigating scientifically what environmental and social impacts blockchain technology will have.

1.3. STRUCTURE

The main body of this thesis is structured into **eight sections**. At the beginning of each section, a brief summary can be found. *Section 1* introduces the topic by setting the context and introducing the aims and objectives. *Section 2* offers an overview of the state-of-the-art of blockchain technology in the field of sustainability, focusing on the environmental impacts of Bitcoin mining and blockchain-based technologies in the supply chain. *Section 3* describes the research design, including identified research gaps and an overview of the research questions, the hypotheses and how they will be addressed. *Section 4* provides an overview of the theories and methods used in the PhD project. *Section 5* details the results of this project regarding the impact of Bitcoin mining. In *Section 6*, the results of the project related to blockchain technology in supply chains are presented. In *Section 7* the results are discussed. Finally, in *Section 8*, the research questions and hypotheses are answered, the contribution of this project is highlighted, and recommendations for future research are listed. Following the main body of the thesis, the *references* section can be found. The appendix contains all *published and submitted papers*.

2. STATE-OF-THE-ART: BLOCKCHAIN TECHNOLOGY AND SUSTAINABILITY

This section provides the state-of-the-art of blockchain technology and sustainability as well as related concepts. Section 2.1 offers an overview of the relevant technical concepts for this PhD thesis. The following section (2.2) describes the state-of-the-art of sustainability in the context of blockchain technology. Section 2.3 then outlines the state-of-the-art of the environmental impacts of Bitcoin mining. In Section 2.4, an overview is provided of the potential for blockchain technology to foster sustainability. Finally, Section 2.5 includes additional insights on a specific use case, namely blockchain technology implemented in supply chains.

2.1. WHAT IS BLOCKCHAIN TECHNOLOGY?

In 2008, Satoshi Nakamoto, an unknown person or group, first published the whitepaper *Bitcoin: A Peer-to-Peer Electronic Cash System* (Nakamoto 2008). In it, a protocol was described that enables the verification of digital assets through the so-called “blockchain.” The blockchain solves the double-spending problem. Before Nakamoto’s whitepaper, it was not possible to verify whether a digital asset had been duplicated and spent several times. The blockchain protocol allows the ownership of a digital asset to be tracked from its inception to its current owner, making digital ownership reliable and unambiguous without requiring the involvement of a trusted third party such as a bank.

Blockchain is a distributed ledger that publicly tracks transactions. This is accomplished through a peer-to-peer network, eliminating the need for an intermediary. This system also means that not one single point of failure exists. If a computer node (e.g. a peer) becomes unavailable, the rest of the network still maintains the ledger and it can continuously be accessed by users. If a peer attempts to manipulate the ledger, the rest of the network will recognize this attempt and reject the corrupt information because a blockchain is an append-only ledger. New information is added in the form of blocks to the end of a chain of blocks

– hence the name blockchain. These blocks are cryptographically linked, and changes to a single character in the blocks will be detected. The cryptographic link is created by running the content of the block through a hashing algorithm that translates any text into a fixed-length number. This fixed-length number – known as a hash – cannot be reverse-engineered. If even a single character in the block were changed, the hash would be completely different. This means that any change in the previous blocks is detected, and since the other nodes in the network have the correct version of the ledger, the manipulated version is simply not accepted. The hash of a block is then included in the following block; this step ensures that any change to accepted blocks will be noticed, making a blockchain virtually immutable.

A consensus mechanism is needed in order to secure the network and verify transactions. In the original Bitcoin protocol, a consensus mechanism called proof-of-work (PoW) was proposed (Nakamoto 2008). The example of Bitcoin is used here to explain PoW. In PoW, so-called miners compete to *mine* the next block and are rewarded with a block reward plus the transaction fees of the transactions contained in the block. In 2009, the block reward was 50 bitcoin (BTC). Every 210,000 blocks, which is about every four years, the block reward is halved (de Vries 2021). In 2021, the block reward is 6.25 BTC. In December 2020, the share of transaction fees in total miner revenue was around 10%, so an additional 0.625 BTC (de Vries 2021). At Bitcoin's peak market price of about $63,000, these rewards translate to almost $435,000 per block mined. At more recent market prices of around $35,000 (June 2021), they translate to $240,000. In order to *mine* a block, the miners undertake a trial-and-error process whereby they continuously change one component in the block they want to add, generating hash after hash in the hope that one of them fits the requirement that the hash is below a pre-determined number. As described before, hashes cannot be reverse-engineered, as one small change in the text leads to a completely different fixed-length number or hash. Thus, mining constitutes a "brute force" attempt to meet the requirements. On May 14, 2021, miners made over 180 quintillion attempts every second of the day, attempting to guess a hash that met the requirements (Blockchain.com 2021c). The number of guesses is also called the hashrate. In other words, on that date, the hashrate was about 180 million tera hashes per second (TH/s). The requirements depend on the difficulty of the system, which, in turn, depends on how high the hashrate is: The higher the hashrate, the greater the difficulty, and the fewer hashes meet the requirements. This is the case to keep the average mining time of a block at about 10 minutes. Consequently, if one miner has a higher hashrate than others, their chances of mining the next block and gaining the rewards are higher. It also means that miners have a strong incentive to add new mining hardware in order to increase their chances of gaining the reward.

In 2019, PoW blockchains represented almost 60% of all blockchains (Schinckus 2020). These blockchains include many cryptocurrencies such as Ethereum (as of July 2021), Litecoin, and Monero. While the general concept of their PoW is the same, they vary to some degree. For example, in the Litecoin blockchain, a new block is added, on average, every 2.5 minutes (Gervais et al. 2016). Other consensus mechanisms have been developed in the past several years. One example is proof-of-stake (PoS), in which the miners are called validators and can win the right to add the new block through a lottery mechanism. In order to ensure that the validators can be trusted, they are required to stake a certain amount of cryptocurrency which is lost if they act maliciously (Schinckus 2020). Since the first bitcoin was mined in 2009, blockchain technology has continuously been adapted, new cryptocurrencies have been created, and the technology has been proposed to solve a wide range of problems outside the financial sector, such as tracking and tracing physical goods through a supply chain. In these contexts, blockchain technology is not a stand-alone technology but part of a system of technology that includes other components such as smart contracts – algorithms that can run on the blockchain – or tracking devices for supply chain implementations (Köhler and Pizzol 2020). Therefore, in the rest of this thesis, when referring to applications that use blockchain, the term *blockchain-based technologies* will be used.

2.2. BLOCKCHAIN TECHNOLOGY AND SUSTAINABILITY

The literature on blockchain technology has increased substantially over the past few years. However, most research is still within computer science, engineering, and business (Xu et al. 2019). Research on the intersection between blockchain technology and sustainability is still in the early stages. Only a few studies investigating blockchain technology from a sustainability perspective have been conducted. Within this domain, the literature can be divided into studies that assess the environmental impact of blockchain technology and those that investigate the potential applications of this technology. It has been questioned whether blockchain technology use and sustainability represent a contradiction – and whether blockchain's growing carbon footprint renders the positive impacts of its applications null and void (Baker 2021). This conflict is evident in how these two streams of literature have emerged, and in the fact that the discussion of blockchain technology's environmental impacts is crucial to the discussion of its applications for sustainability.

The literature on blockchain technology's energy consumption and associated environmental impacts can be considered more mature, as it has grown steadily over the past few years. The first estimates of Bitcoin's energy consumption were made as early as 2014 (Malone and O'Dwyer 2014). Since then, the literature has extended to estimate the carbon footprint associated with energy consumption (de Vries 2018; Köhler and Pizzol 2019; Stoll et al. 2019), assess different cryptocurrencies (Krause and Tolaymat 2018; Li et al. 2018), and further analyze the underlying market mechanisms (de Vries 2021).

In contrast, the discourse on the sustainability of blockchain-based technologies generally remains nascent and is mainly based on the discussion of potentials. The literature assesses blockchain technology's potential for addressing environmental challenges (Chapron 2017), human rights (Al-Saqaf and Seidler 2017), and the Sustainable Development Goals (Aysan et al. 2021). Kewell et al. (2017) propose the notion of "blockchain for good" as an emerging phenomenon, but only a few articles have been published using this terminology. Sustainability and blockchain are further discussed separately in relation to specific applications, e.g. blockchain for sustainable supply chains (Kouhizadeh and Sarkis 2018) and blockchain for the circular economy (Upadhyay et al. 2021).

One point the studies agree upon is that blockchain technology could be a "game-changer", benefitting societies, helping them to become more sustainable, and serving as a potential catalyst for achieving the Sustainable Development Goals (Chapron 2017; Voshmgir et al. 2019). The literature also agrees that while technology can play a critical role in tackling sustainability challenges, it needs to be designed to do so

(Al-Saqaf and Seidler 2017; World Economic Forum 2018). As Kranzberg's first law of technology states *"Technology is neither good nor bad nor neutral"* (Kranzberg 1986). Thus, blockchain technology can only bring the anticipated improvements if it is consciously designed that way. Such a conscious design requires decisive action with continued management of the unintended consequences, and risks and the responsibility should be shared by all stakeholders (World Economic Forum 2018). Since the technology is still in early stages and different features are currently being built, it is crucial that system designs are tested in an ethical manner and without harming beneficiaries (Zwitter and Herman 2018).

2.3. THE IMPACT OF BITCOIN MINING

The literature on Bitcoin mining and its related energy consumption and carbon footprint has grown over the past years, both in the number of articles published and in their quality. Early publications on the topic were mainly in grey literature, yet a recent shift toward academic literature can be seen. The first estimation of Bitcoin's energy consumption was published in 2014 by Malone and O'Dwyer – five years after the first Bitcoin block was mined. The researchers estimated the energy consumption of Bitcoin mining to be between 0.88 and 87.60 TWh per year (Malone and O'Dwyer 2014). This was followed by a number of grey literature articles on the topic (AlliedControl 2014; Malmo 2015; Deetman 2016; Zohair 2017), estimating Bitcoin's energy consumption to be somewhere between 1.88 and 7.8 TWh per year.

Figure 1 provides an overview of the relevant contributions to estimating Bitcoin mining's energy consumption since 2016[1]. The figure also shows in grey the hashrate over the same period. While the hashrate in early 2018 was slightly over 15 million TH/s, it grew to over 180 million TH/s in May 2021 and fell again to 90 TH/s in July 2021 (Blockchain.com 2021c). This is one of the main parameters demonstrating the growth of Bitcoin mining over the past years. It

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[1] *All values are listed under the year they were reported for, not when they were published. Following studies are included:* Digiconomist 2021; CBECI 2021; *de Vries 2018, 2019, 2020, 2021; Vranken 2017; Valfells and Egilsson 2016; Krause and Tolaymat 2018; Zade et al. 2019; Stoll et al. 2019; Gallersdörfer et al. 2020; Bevand 2017.*

should be noted that both Digiconomist (2021) and the Cambridge Centre for Alternative Finance (CBECI 2021) provide continuous Bitcoin Energy Consumption indices, while the other studies provide snapshots of specific points or periods in time. It should also be highlighted that de Vries is the individual behind Digiconomist. In addition to the overview in Figure 1, Jiang et al. (2021) project that without interventions, the energy consumption of Bitcoin mining in China will peak in 2024 at 297 TWh before miners move to cheaper locations.

The figure indicates that the estimates of Bitcoin's energy consumption for mining have continuously increased over the years. Short-term dips can be observed, but an overall upward trend is portrayed. The most recent dip in summer 2021 is most likely due to policy changes in China. It is expected that the hashrate will recover, but it is too early to say if and how this will, in fact, occur. While the values differ between the studies, they are within the same order of magnitude. It should be highlighted that there are two main approaches to estimating Bitcoin mining energy consumption: an economic approach and a technical approach.

Through the technical approach, it is possible to develop fairly accurate assessments of the lower and upper bounds of energy consumption using the available data on the network's hashrate and the efficiency of the mining equipment. For example, multiplying the energy

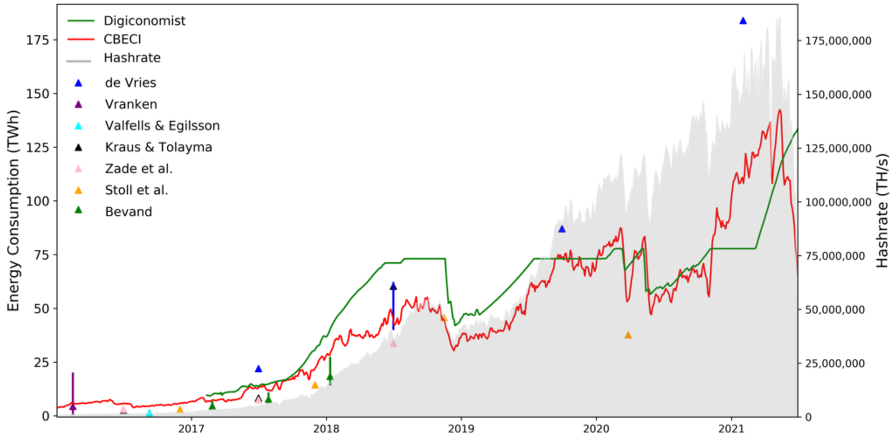

Figure 1: Overview of studies and data on Bitcoin's energy consumption from January 2016 to June 2021[1]

consumption of the most efficient hardware available at a given point in time with the network's hashrate makes it possible to determine the energy consumption in a best-case scenario for that point in time. Similarly, by using data on the energy consumption of hardware that is at the lower end of efficiency, an upper bound can be estimated. Malone and O'Dwyer (2014) used this approach in 2014, and Bevand (2017) subsequently added an in-depth analysis of the efficiency of mining equipment. Digiconomist (2021) used this methodology to provide an assessment of the lower bound – not shown in Figure 1. The *Bitcoin Energy Consumption Index* by the Cambridge Centre for Alternative Finance also uses the technical approach to estimate both the upper and lower bounds – also not portrayed in Figure 1 (CBECI 2021). While upper and lower bounds use unrealistic assumptions to obtain the range of possible results, it is possible to use the same method with more precise assumptions, considering factors such as the energy requirements for cooling to estimate best guess results. Notable studies that have taken this approach include the best guess scenario of the Cambridge Centre for Alternative Finance (CBECI 2021), Köhler and Pizzol (2019), and Stoll et al. (2019).

The economic approach to assessing Bitcoin's energy consumption instead focuses on the profitability of miners. Bitcoin's market price directly affects the miners' revenue, as it determines the value of the mined coins and transaction fees. Since Bitcoin is a competitive market, economic theory states that mining one bitcoin will cost one bitcoin (de Vries 2021). When taking an economic approach, assumptions need to be made about the electricity costs for miners, as electricity is the main cost factor for Bitcoin mining operations. This allows an estimation of the energy consumption at a given market price. This approach is more flexible to short-term changes in market price and profitability, but it also depends on assumptions of electricity costs for mining in different locations. The economic approach has been used mainly by de Vries (2018, 2019, 2020, 2021) – and, thus, by Digiconomist (2021).

PoW, and thus Bitcoin, is designed to consume extensive energy and incentivizes increasing energy consumption. As the total amount of computational power in the network grows, the share of each individual mining device declines; consequently, the expected number of blocks mined per device declines as well. This means that the first miner to use a new device has a significant competitive advantage over the others (de Vries 2021). During a phase of market decline, only the most efficient devices running on cheap electricity are kept operating and the theoretic optimum is approached (de Vries 2020). This is different during phases of market growth, which was the dominant condition over the past few years. Increased profitability leads the actors in the market to further invest in hardware. They can either purchase new and more efficient devices or old and less efficient ones. While new equipment seems preferable, it may not be readily available during peak growth phases. For example, in early 2021, Bitmain, one of the major mining device producers, had already sold out through August 2021 (de Vries 2021). Older devices can be more readily available and cheaper to buy. Mining facilities may also still have devices that were previously deemed unprofitable. In the short-term, these older, less-efficient devices will be used to compete in the growing network, while in the long run, the newer devices will become more dominant (de Vries 2020). When large numbers of new devices are purchased during times of growth, they “lock in” an increase in energy consumption for when these devices are delivered, sometimes months later, as the purchases cannot be canceled or refunded (de Vries 2021). There is also a potential shortage of semiconductors for the mining hardware, as these are key components for other technologies as well. Since Bitcoin mining hardware requires a substantial number of semiconductors, this shortage is exacerbated (de Vries 2021), leading to a limited supply of equipment and potentially further incentivizing the use of older hardware.

Energy consumption alone, however, does not fully show the impact of Bitcoin mining. An examination of the cryptocurrency’s environmental footprint is needed. Fewer estimations have been made of Bitcoin’s carbon footprint than of its energy consumption. Initially, these estimations were conducted with primitive methods, which have improved over time. For example, Digiconomist (2021) initially assumed that 70% of Bitcoin mining happened in China and the remaining 30% had no environmental impacts. Further, the estimations only include the carbon footprint of electricity consumption, neglecting other impacts. Table 1 provides an overview of the carbon footprint estimations of Bitcoin mining in the literature.

Table 1: Carbon footprint estimates of Bitcoin mining in the literature in $MtCO_2$

Year	**Krause & Tolaymat 2018**	**Foteinis 2018**	**Mora et al. 2018**	**Stoll et al. 2019**	**de Vries 2019 & 2021**
2016 – mid-2018	3-13				
2017		43.9	69		
2018				22 – 22.9	19 – 29.6
2019					
2020					
2021					90.2

Krause and Tolaymat (2018) calculated the carbon footprint of Bitcoin mining for the period between 1 January 2016 and 30 June 2018 to be 3-13 Mt CO_2. They used different country-specific scenarios to obtain a range of possible impacts, with the Canadian electricity mix representing the lower bound and India as the upper bound. Other country-specific electricity mixes the researchers tested included China and the USA. It is unclear why the specific countries were chosen.

The results from Foteinis (2018) include both Bitcoin and Ethereum mining. It is not possible to currently replicate the results as the link to the methods and data no longer works (as of 2021). Since the original article is a short correspondence, it is unfortunately of limited value at this point.

Mora et al. (2018) made the controversial statement that Bitcoin usage alone would emit enough carbon dioxide emissions to push the planet above 2°C within less than three decades (Mora et al. 2018). The study estimated that in 2017, the carbon footprint of Bitcoin was 69 $MtCO_2$-eq. Depending on the assumed growth rate, Bitcoin could warm the planet by 2°C within 11-22 years. However, this study has been heavily rebutted. Houy (2019) stated that the numbers provided by Mora et al. were overestimated by a factor of 4.5. Dittmar and Praktiknjo (2019) further pointed out the structural limitations of the study. Masanet et al. (2019) stated that more rigor and greater analytical care were needed, as Mora et al. not only used outdated values for mining hardware efficiencies and CO_2 intensities of electricity consumption but also described sudden and improbable departures from historical trends in Bitcoin transactions. An assessment with updated values by Masanet et al. (2019) led to a quarter of the original result.

More robust results were presented by the study from Stoll et al. (2019). They localized over 2,000 mining devices via their IP addresses and identified mining locations in the US (19%), Venezuela (16%), Russia (11%), Korea (7%), Ukraine (5%), and China (4%). Additionally, they estimated the geographical distribution of miners based on mining pools, concluding that 68% were located in Asia, 17% in Europe, and 15% in North America. The remaining 21% could not be localized. For the Chinese miners in this model, a split between hydro-rich and coal-heavy regions was assumed and a weighing between the regions was included. Using the device IP method, the researchers estimated Bitcoin mining's carbon footprint to be 22 $MtCO_2$, with the mining pool method producing 22.9 $MtCO_2$. The device IP method allowed the identification of new locations that were previously not seen but also presented downsides. Not all devices can be detected by this method, as some miners may use TOR or VPN to obscure their actual location. Further, the study specifically looked at Bitmain devices, while other devices appear to be excluded. While this approach may have provided accurate results, it is impossible to know for certain as it could not be identified how many miners disguised their IP location and where miners using different devices were located.

de Vries (2019) calculated Bitcoin's carbon footprint for 2018 using an average of 475 gCO_2-eq/kWh. This calculation was based on data from his *Bitcoin Energy Consumption Index* (Digiconomist 2021). While this index provides continuous data on the energy consumption of Bitcoin mining, the carbon footprint is only reported for the day the page is visited. According to Digiconomist (2021), a distribution of 70% of miners in China and 30% completely emissions-free miners in other locations was initially assumed. Using this method, a weighted carbon intensity of 490 gCO_2-eq/kWh can be derived. However, the methodology has evolved since this calculation. Rauchs et al. (2018) identified a more detailed geographical distribution of miners, including 47.6% in China, 25.8% in Georgia, 11.6% in the USA, 7.7% in Canada, 4.3% in Sweden, and 2.1% in Iceland. This resulted in a weighted carbon intensity of 475 gCO_2-eq/kWh. For his 2021 study, de Vries assumed again a carbon intensity of 490 gCO_2-eq/kWh, in line with the implied carbon intensity of Stoll et al.'s (2019) study of 480-500 gCO_2-eq/kWh.

An important issue in the discussion of the carbon footprint of Bitcoin mining is the use of renewable energies to power the mining equipment. In their 2018 report, CoinShares stated that the majority of miners in China were located in Sichuan province, where hydropower is abundant. In the report, they stated that 77.6% of mining was powered by renewable energies (Bendiksen et al. 2018). However, this assessment does not align with miner location data from other sources, such as Rauchs et al. (2018), who reported that only 28% of mining equipment was powered by renewable energies. There have been increasing reports about Bitcoin spurring fossil fuel energy productions. For example, an old Australian coal power plant was reopened after it had been closed since 2014 (Schinckus 2020). In 2018, Hydro-Quebec decided to impose a moratorium on new crypto mining operations after significant numbers of miners threatened to destabilize their local electricity grid (de Vries 2021). Recent growth in cryptocurrency mining has also been observed in Iran, where miners mostly use oil-fueled electricity (de Vries 2021). Information on the locations of and electricity sources for mining are still scarce, and transparency from the Bitcoin mining industry would improve the research.

Besides the carbon footprint, concerns have been raised about other environmental damages. Bitcoin mining equipment is only produced for the singular task of mining. It is estimated that the mining rigs are used for about 1.5 years before becoming obsolete. This would generate e-waste of about 10.95 metric tons (de Vries 2020), or about 135 g of e-waste per transaction (de Vries et al. 2021). Goodkind et al. (2020) also estimated the per coin economic damages of air pollution and associated human mortality and climate impacts resulting from mining for both China and the US. They concluded that for the year 2018, each \$1 of Bitcoin value created resulted in \$0.49 in health and climate damages in the United States and \$0.37 in China.

2.4. APPLICATIONS OF BLOCKCHAIN TECHNOLOGY

Blockchain technology has been proposed as a tool to address sustainability through various applications. The technology is expected to particularly increase trust, provide transparency, reduce power asymmetries, increase accountability, and incentivize sustainable behavior (Voshmgir et al. 2019). Figure 2 provides an overview of several different applications for sustainability that have been identified

Figure 2: Overview of potential applications of blockchain technology to foster sustainability

from a variety of reports and articles (Kewell et al. 2017; World Economic Forum 2018; Horner and Ryan 2019; Voshmgir et al. 2019). Some of these applications may overlap, and this clustering does not claim to include every possible application for sustainability; rather, it includes the main expected application potentials of blockchain technology based on the literature. Furthermore, this overview is merely a collection of the identified potentials rather than an assessment of if and how these potentials can be achieved.

Self-Sovereign Identity. Between one and two billion people in the world do not have a legally recognized identity (Kewell et al. 2017; Voshmgir et al. 2019). This is an issue because an individual's lack of identity often means that they cannot own property, move freely between regions and countries, or gain access to financial services (Voshmgir et al. 2019). Self-sovereign identity management systems based on blockchain technology have gained interest in recent years (Wang and Filippi 2020). Such solutions could be more flexible and efficient, particularly in countries with fragile institutions, and contribute to securing fundamental human rights for billions of people (Wang and Filippi 2020). Self-sovereign identities can also help reduce the disparities between people who currently lack access to basic services requiring an identity and the rest of the world. A blockchain-based self-sovereign identity could further be important regarding two applications: *financial inclusion* and *ownership recognition*.

Financial Inclusion. Similarly as with the lack of legally recognized identities, there are still an estimated two billion people without access to traditional banking services, e.g. bank accounts, credit, or insurance (Voshmgir et al. 2019). Blockchain-based technologies could address these issues. Significant benefits are expected from automation, disintermediation, low costs, and high security of such a solution. Blockchain-based technologies could reach remote communities and connect them amongst themselves, within their country, or even internationally (Kewell et al. 2017). Sending remittances using digital tokens can be significantly cheaper than using established services. While fees for Bitcoin or Ethereum can be high, there are low-cost solutions, such as Ripple (Rella 2019). Furthermore, these transactions can be almost instantaneous (Voshmgir et al. 2019). Digital tokens can also be used to allow the underbanked to gain access to loans. While billions of people are high-risk clients for traditional banks or live too far away from a local branch, blockchain-based technologies can allow them to obtain loans and maintain a record of the transactions and credit repayments connected to their digital identity (Wang and Filippi 2020). Building records in such a secure way can help these individuals access financial services and cheaper rates in the future.

Ownership Recognition. Blockchain-based technologies can also be used to build a registry of ownership for, e.g. land titles or birth certificates (Chapron 2017; Kewell et al. 2017). This ensures that these records are securely stored, transparent, and immutable. A birth certificate could be attached to a self-sovereign identity, while the transfer of ownership of e.g. land titles can be securely handled through smart contracts. The seller can create a contract that states that ownership will be transferred as soon as a specific amount of money is received. Once this condition is met, the contract is automatically solved. The seller receives the money, and the buyer receives the ownership right. Within this system, there is no risk of not getting paid or not receiving the certificate of ownership. Additionally, there is a record of the transaction. While a blockchain-based ownership registry may still be undercut by, e.g. armed aggressors, it could limit the eviction of local populations and strengthen their ability to fight for their rights (Chapron 2017; Kewell et al. 2017).

Corruption Prevention. A blockchain ledger is not anonymous. It is pseudonymous. While it may not be easy to identify who is behind a pseudonym, it is possible to track the tokens and certificates. This can be particularly useful for tackling corruption (Willrich et al. 2019). Transactions that are caught within the system can be audited, and it is more difficult for users to hide anything when disclosing finances or information, as the information on the blockchain cannot be retrospectively changed. Blockchain technology further eliminates opportunities for falsification (Voshmgir et al. 2019). Certificates, e.g. for sustainably certified coffee, cannot be multiplied, guaranteeing that only the certified amount can be sold as such.

Sustainability Monitoring. Similarly, the immutable and transparent nature of blockchain technology can be leveraged to measure impacts and increase accountability. For example, government actions to reduce carbon emissions could be measured, made transparent via the blockchain, and automatically assessed (Voshmgir et al. 2019). Furthermore, companies are under pressure to increase their sustainability and prove their environmental and social credentials. Current self-reporting could be improved with blockchain, allowing for verification from third parties. Companies could be incentivized to provide this kind of data via tokens (World Economic Forum 2018). Another possibility would be the use of one single blockchain for data from certification bodies, which could increase the transparency and authenticity of this data (World Economic Forum 2018). Data collection and management could be further automated with the use of additional technologies, such as sensors to monitor air quality (Horner and Ryan 2019). Overall, these changes could lead to more real-time reporting, less bureaucracy, and more sustainability (Horner and Ryan 2019). Similar mechanisms could be used for the assessment of an individual's impact. For example, a person could track their own footprint, sustainable behavior could be rewarded, and the impacts of behavior could be better understood (Voshmgir et al. 2019). This kind of gamification of individual – but also government or company – actions could be one tool to address sustainability challenges and encourage behavior changes.

Transforming Markets. Blockchain technology can be a tool to transform markets. Market-based approaches to managing the environmental challenges that stem from externalities and the market failures of existing markets (e.g. pollution) can be optimized through the use of this technology (World Economic Forum 2018). This is particularly important because current markets are sometimes viewed skeptically due to the lack of transaction visibility and traceability, as well as potential double-counting (World Economic Forum 2018). Blockchain technology has been applied to the Chinese carbon market, reducing costs and increasing transparency, auditability, and credibility (Eikmanns 2018). A cap-and-trade system was established and automatized, avoiding the over- or undersupply of certificates (Eikmanns 2018). Additionally to such a system, an escrow mechanism could be implemented using blockchain technology. For every greenhouse gas emitted, a company would need to deposit money on the blockchain. The funds then would only become available when the emissions were sequestered, e.g. through reforestation or carbon capture mechanisms (Eikmanns 2018). Furthermore, trading of carbon offsets or allowances could also be used on the individual or household level (World Economic Forum 2018).

Energy Trading. Currently, the main strategy for ensuring grid stability due to the rising shares of volatile renewable energies is curtailment (Voshmgir et al. 2019). In such a system, blockchain technology could increase the transparency of electricity sources and certificates (Voshmgir et al. 2019). However, the real potential of blockchain technology is considered to be its application to decentralized electricity trading. Peer-to-peer trading becomes feasible as platforms enable the local sale and purchase of electricity without the need for central authorities and middlemen (Kewell et al. 2017; Eikmanns 2018; Horner and Ryan 2019). Blockchain technology can be used to ensure a transparent, auditable, and automated marketplace that settles transactions within minutes (Horner and Ryan 2019). Additionally, such systems are considered to be more resilient to storms and reduce the loss of fugitive emissions and the costs of consuming electricity while also empowering communities (Horner and Ryan 2019).

Circular Economy. Blockchain technology has further been proposed to overcome some of the current barriers to implementing the circular economy (Böckel et al. 2021). The technology could be the main infrastructure for information sharing and collaboration, which are considered essential for circular economy concepts to succeed (Böckel et al. 2021). Thereby, blockchain technology could contribute to initiatives such as the sharing economy, the market for secondary materials, reverse logistics, and changing consumer behavior (Kouhizadeh et al. 2019). Narayan and Tidström (2020) have further identified the potential of tokens on a blockchain to support operationalization and optimization in transitioning to circular models of value creation and appropriation.

Supply Chain Management. Blockchain technology is considered to create benefits, particularly related to traceability, recording ownership over time, authenticity, transparency, and trust (Chapron 2017; Kewell et al. 2017; Eikmanns 2018). Since it is beyond the scope of this thesis to investigate all applications with potential benefits for sustainability, the focus is placed on supply chain management. Blockchain-based technologies in supply chains have been chosen as a case study for several reasons. First, the potential within supply chain management has been identified early (Gurtu and Johny 2019). Therefore, applications within this field are manifold and further developed than some of the other blockchain-based technology applications. Furthermore, applications within supply chain management involve various potentials of blockchain technology, including traceability, use of financial services, and secure data transfer. Finally, a life cycle perspective can be applied to blockchain-based technologies in supply chain management since products are considered from the source to the consumer. The state-of-the-art of blockchain-based technologies in supply chains will be examined in the next section, and the applications in supply chain management will be investigated as a use case throughout this thesis.

2.5. BLOCKCHAIN-BASED TECHNOLOGIES IN SUPPLY CHAINS

Until recently, little had been published about the implementation of blockchain-based technologies in supply chains, yet the research has grown significantly over the past few years (Gurtu and Johny 2019; Queiroz et al. 2019). Even as the research is gaining momentum, the literature agrees that blockchain-based technologies in supply chains are still in their infancy (Queiroz et al. 2019; Wang et al. 2019; Lim et al. 2021). Blockchain-based technology projects are mostly in pilot or early stages with limited evidence of large-scale adoption and limited empirical evidence on how blockchain technology is beneficial in practice (Queiroz et al. 2019; Wang et al. 2019). Thus, the research remains at the sensemaking and explorative stage, with a limited understanding of the technology's impact on supply chains (Wang et al. 2019; Lim et al. 2021).

In their literature review, Wang et al. (2019) describe how previous research has mainly focused on four areas: describing previous pilots and how they have been implemented; conceptually addressing the potentials of blockchain technology in supply chains; predicting how blockchain technology will be used in supply chains; and proposing how blockchain technology could solve problems with contemporary supply chains. Lim et al. (2021) go into more depth in their literature review and identify three themes concerning the current research: 1) The research concentrates on explaining the value, challenges, and opportunities of implementing blockchain technology. 2) Most studies investigate where blockchain technology can affect supply chains and which function the technology can adopt. 3) Few articles focus on how the technology needs to be configurated for specific implementations (Lim et al. 2021). The literature review also presents the different methodological approaches of the existing studies. Most of the literature falls under the conceptual category, while fewer articles take an empirical or modeling approach. The smallest number of studies focus on system implementation, determining how blockchain technology is deployed (Lim et al. 2021).

Blockchain technology has been proposed to increase trust in supply chains by preventing adversarial behavior, such as fraud, and by increasing transparency (Wang et al. 2019). The technology can be used to integrate many different actors into one secure network (Gurtu and

Johny 2019). Specifically, blockchain technology brings value in four different areas: extended visibility and traceability; supply chain digitalization and disintermediation; improved data securing for information sharing; and smart capabilities (Wang et al. 2019). In addition, the technology addresses currently existing problems in supply chains, such as data silos, the opacity of information, and the difficulties of product tracking (Lim et al. 2021).

Extended visibility and traceability can be facilitated by blockchain technology. A chain of custody can be constructed by registering every change in ownership or product composition (Wang et al. 2019; Lim et al. 2021). Other data, such as product attributes or environmental data, may also be included (Wang et al. 2019; Lim et al. 2021). This creates visibility within the supply chain, but also – if the data is shared – with other actors such as auditing bodies, consumers, or the public. The auditing process can particularly benefit from additional information and potentially generate efficiencies (Queiroz et al. 2019). Blockchain technology can further allow the real-time tracking of products (Gurtu and Johny 2019; Wang et al. 2019). Ultimately, visibility and traceability increase transparency, accountability, and trust not only within the supply chain but also for consumers and the public (Wang et al. 2019; Feng et al. 2020; Lim et al. 2021).

Supply chain digitalization and disintermediation are fostered with blockchain-based technologies. Blockchain technology has been suggested to drive the digitization of paper-based processes (Wang et al. 2019). However, this is not due to blockchain technology; rather, the implementation of blockchain-based technologies requires digitized processes. Through peer-to-peer networks, blockchain-based technologies remove middlemen, thereby facilitating faster and more direct interactions in the supply chain (Lim et al. 2021). In a pilot, Walmart demonstrated that using blockchain technology allowed them to identify the origin and journey of a mango within seconds, whereas it had previously taken them 6.5 days (Kamilaris et al. 2019).

Improved data security for information sharing is enabled by the immutable blockchain ledger. It guarantees the integrity and security of the data and establishes a shared record of all transactions in real time (Wang et al. 2019; Lim et al. 2021). Falsifying records becomes more difficult, as it can only be done at the point of data entry (Wang et al.

2019). This makes corruption and fraud attempts more challenging (Queiroz et al. 2019). Through cryptography, blockchain technology can further enhance the secure sharing of data among supply chain actors. Chosen data can additionally be made available to specific groups, such as certification bodies or customers (Wang et al. 2019). Blockchain-based technologies can be more resilient than existing alternatives.

Smart capabilities are sometimes proposed to be the most transformative advancement of blockchain-based technologies (Wang et al. 2019). So-called smart contracts – computerized transaction protocols – execute automatically when the terms of a contract are met (Lim et al. 2021). For example, one buyer will pay the smart contract the agreed-upon amount, but only when the buyer receives the product will the seller be able to access the funds, eliminating any issues surrounding withheld payments (Wang et al. 2019). This system may be able to reduce costs and delays of payments (Lim et al. 2021). Similar examples of automation and self-execution are expected to offer significant efficiencies (Lim et al. 2021). Processing times can be reduced from the previous 7-10 days to 1-4 hours (Wang et al. 2019).

Wang et al. (2019) further highlight in their literature review that the challenges of implementing blockchain technology persist. There are technical challenges, such as latency, meaning that it may take a long time to verify a transaction, the difficulty to reverse real mistakes, and issues of interoperability (Wang et al. 2019). Interoperability issues are both viewed as a challenge and a chance for blockchain technology, as it is hoped that different applications could run on various blockchains and communicate with other applications in the long-term (Ge et al. 2017). Organizational and user-related challenges include the fear of intermediates being removed from their roles and the opposition to transparency from some actors (Wang et al. 2019). Some actors benefit from intransparency and the need for intermediaries, and they are, naturally, not interested in changing these conditions. Finally, operational challenges involve the need to include all actors in the supply chain, which can be a difficult and complex task (Wang et al. 2019). These actors need to agree on various aspects, such as how the data should be stored and who will cover which of the costs of setting up a new system. It can also be challenging to accurately mirror the physical movement of a good on the blockchain (Wang et al. 2019), particularly when it is a fungible, i.e. non-unique, good such as coffee beans or a chocolate bar.

While general research on blockchain technology in supply chains has significantly increased, there is still little research on blockchain technology and sustainable supply chains (Kouhizadeh and Sarkis 2018; Queiroz et al. 2019; Wang et al. 2019; Lim et al. 2021). It is a common sub-theme in articles, but few focus specifically on this topic. An early study by Kouhizadeh and Sarkis (2018) suggests different use cases for applying blockchain technology to sustainable supply chains. Chandan et al. (2019) illustrate how blockchain could help supply chain sustainability.

Upstream companies have a significant influence on overall supply chain sustainability. With blockchain-based technologies, historical vendor performance and sustainability data can be made available to them, providing them with the opportunity to select vendors at different stages of the supply chain (Kouhizadeh and Sarkis 2018). These upstream companies have the tools to implement sustainability training programs with their vendors. Using smart contracts, the vendors can be held accountable to implement learnings and be rewarded when they meet specific targets, e.g. environmental performance measurements (Kouhizadeh and Sarkis 2018). Products and material data can be kept on the blockchain. Besides transactional characteristics and historical data, data on quality, recyclability, and carbon footprints can be attached as well (Kouhizadeh and Sarkis 2018; Chandan et al. 2019). This can help companies and consumers make more informed purchasing decisions. Blockchain-based technologies can further support companies with accumulating, aggregating, and certifying documentation, which in turn can make auditing more efficient or even redundant, as the data can be continuously evaluated and updated (Kouhizadeh and Sarkis 2018; Chandan et al. 2019). The data that is collected throughout the supply chain can also be used for life cycle assessments (LCA). Data collection can occur automatically, the data quality can increase, and actual data from the specific supply chain can be used for LCA modeling instead of generic datasets (Kouhizadeh and Sarkis 2018; Chandan et al. 2019). Furthermore, real-time data can help reduce wastage throughout the supply chain (Chandan et al. 2019).

3. RESEARCH DESIGN

This section first provides an overview of the research gaps identified in Section 2 that this project addressed (Section 3.1). Section 3.2 summarizes the purpose of the study, the research questions, and the hypotheses. This section also shows how the studies conducted in the PhD project address the research questions and hypotheses.

3.1. RESEARCH GAPS

Section 2 describes the state-of-the-art of the research on blockchain technology and sustainability. The section further helps to identify research gaps that have yet to be addressed.

There are several research gaps regarding the energy consumption and environmental footprint of Bitcoin mining. First, the energy consumption and impact estimations are not always peer-reviewed, and the results are not replicable in several cases. When the PhD project started, the energy consumption and carbon footprint of Bitcoin mining were mainly discussed in grey literature. This has changed over time with the increased presence of the topic in academic literature. However, even within academic literature, studies exist that cannot be reproduced. For example, the link to the methods and data section of the study by Foteinis (2018) is no longer accessible. Second, no standard method and data for calculating the carbon footprint is used. Digiconomist (2021) developed his first calculations of the carbon footprint of Bitcoin mining using the assumption that 70% of miners are located in China, with the rest of the electricity assumed to be impact-free. Many studies (de Vries 2019, 2021; Stoll et al. 2019) obtain their results from one specific day and annualize these to report the energy consumption and carbon footprint for an entire year. However, a calculation from January 2018 and one from October 2018 will lead to significantly diverging results for the same year. Thus, the comparability of the results is limited. Third, the studies only assess the carbon footprint of energy consumption; no other parameters are included. The production and end-of-life (EoL) of the mining equipment are neglected in existing studies. Furthermore, no impact categories besides the carbon footprint are considered. Most importantly, a life cycle perspective is needed. Considering environmental impacts throughout the life cycle of Bitcoin mining can help prevent these impacts from being unintentionally shifted elsewhere within the life cycle. Another research gap is that existing studies do not identify mining hotspots. Hotspot analysis can be a useful tool to address impacts. Finally, few sensitivity and uncertainty analyses exist. Considering the scarcity of data on mining locations, this is of significant importance. Stoll et al. (2019) included upper and lower bounds for the carbon footprint, and de Vries (2021) performed a sensitivity analysis of electricity prices for his economic approach to calculate the energy consumption of Bitcoin mining. However, detailed sensitivity and uncertainty analyses of all parameters are missing.

Research gaps were also identified regarding the role of blockchain-based technologies in sustainable supply chains. This field of research is still nascent and under-investigated (Tsolakis et al. 2020; Lim et al. 2021). Holistic assessments of sustainability and blockchain-based technologies in supply chains are particularly absent, as current studies mostly focus on a single aspect such as environmental impacts (Lim et al. 2021). An additional research gap involves the one-dimensional analysis of the environmental dimension of sustainability within blockchain-based technologies in supply chains. Most research focuses on “green” supply chains or reducing carbon emissions (Lim et al. 2021), and a broader approach is needed. Additionally, while most of the literature investigates the potentials of implementing blockchain-based technologies in supply chains, there is limited research on actual cases. Little is known about sustainability from real implementations. Case studies in particular can be considered in order to learn from specific experiences (Lim et al. 2021). Empirical research is also required and should involve many groups, such as individuals from different industries and countries, to gain a more holistic view (Lim et al. 2021). There is a further lack of research investigating how value is created, captured, and distributed in blockchain-based technologies in supply chains (Wang et al. 2019). Finally, as blockchain-based technologies adopt the role of sustainability governance mechanisms within supply chains, there is insufficient research studying how blockchain-based technologies relate to existing solutions. Blockchain-based technologies in supply chains are often considered separate from what is already implemented. However, this is an interesting assumption, as these technologies may be applied to the same supply chains that are already governed by other mechanisms, such as voluntary sustainability standards.

3.2. RESEARCH QUESTIONS

The purpose of this PhD project is to investigate and anticipate the environmental and social impacts of blockchain technology "beyond the hype" and with a solid scientific basis.

The **Main Research Question** is, therefore, as follows:

> *What are the environmental and social impacts of blockchain technology?*

The Main Research Question is answered by validating the following **Main Hypothesis**:

> *While the first iteration of this new technology – namely Bitcoin and the proof-of-work consensus mechanism – is detrimental for the planet, blockchain technology can be used as a tool to foster sustainability.*

As the Main Research Question is very broad, it can be broken down into two sub-questions that are used to address the Main Research Question.

Research Question 1:

> *What is the environmental impact of (PoW) blockchain technology from a life cycle perspective based on the example of Bitcoin?*

The goal is to focus on the mainstream financial applications of blockchain as a case study and conduct a quantitative environmental assessment of Bitcoin. A series of factors should be taken into account in this analysis, such as the function of Bitcoin, the growth rate and scale of the Bitcoin blockchain, the mining hardware, and the location of Bitcoin miners. This study aims to improve the validity of analyzing the environmental impacts of Bitcoin mining, as current methods of analysis are arbitrary and not scientifically validated. The study uses life cycle assessment (LCA) and established databases. The analysis will reveal hotspots of environmental impacts; these will be analyzed and suggestions to reduce these impacts will be explored. Research Question 1 is thus answered by validating **Hypothesis 1**:

> *LCA can provide a holistic, solid, and scientific assessment of the environmental impacts of Bitcoin mining.*

Research Question 2:

> *How can blockchain-based technologies foster sustainability based on the example of applications in supply chains?*

The idea behind this question is to examine how blockchain technology can improve the sustainability of supply chains as a case study of applying blockchain technology. It is beyond the scope of this study to examine all potential applications. Therefore, supply chain applications are chosen as one of the promising implementations. One way of examining how blockchain technology can improve the sustainability of supply chains is by focusing on specific case studies, allowing for a deeper analysis and more detailed insights. The goal of examining the case studies is to identify benefits and implications that are potentially transferable to additional cases. Furthermore, a series of in-depth, semi-structured interviews are conducted with stakeholders of blockchain-based technologies in supply chains (e.g. startups developing blockchain technology for supply chains and companies implementing the technology), aiming to identify industry-wide benefits and implications. Research Question 2 is thus answered by validating **Hypothesis 2**:

> *By taking a systemic perspective, it can be assessed if and to what degree blockchain-based technologies bring positive social and environmental impacts.*

Table 2 summarizes the research questions, hypotheses, state-of-the-art, and research gaps that this project aims to address.

Table 2: State-of-the-art and the research gaps addressed by the research questions

Research questions	Hypotheses	State-of-the-art	Research gap
What are the environmental and social impacts of blockchain technology beyond the hype and with a solid scientific basis?	*While the first iteration of this new technology – namely Bitcoin and the proof-of-work consensus mechanism – is detrimental for the planet, blockchain technology can be used as a tool to foster sustainability.*	- Early stages of the blockchain and sustainability discussion - Clear distinction between the discussions of the impact of Bitcoin mining and sustainable blockchain-based technologies	- Missing foundation for sustainability discussion
1. What is the environmental impact of (PoW) blockchain technology from a life cycle perspective based on the example of Bitcoin?	*LCA can provide a holistic, solid, and scientific assessment of the environmental impacts of Bitcoin mining.*	- Bitcoin mining electricity consumption between at least 1 TWh in 2014 and 184 TWh in 2021 - Bitcoin mining carbon footprint between 3 $MtCO_2$ for 2016 to mid-2018 and 90 $MtCO_2$ in 2021 - Findings not (always) peer-reviewed - Results are often not replicable	- No standard method or data - No life cycle perspective (only impact of electricity consumption considered) - Lack of sensitivity and uncertainty analyses
2. How can blockchain-based technologies foster sustainability based on the example of applications in supply chains?	*By taking a systemic perspective, it can be assessed if and to what degree blockchain-based technologies bring positive social and environmental impacts.*	- Main potentials in four areas: 1) extended visibility and traceability; 2) supply chain digitalization and disintermediation; 3) improved data securing for information sharing; and 4) smart capabilities	- Limited number of real cases and experiences investigated - Limited focus on *how* potentials can be fulfilled - Lack of research focusing (holistically) on sustainability - Lack of research relating to existing solutions

Table 3 provides an overview of the ways this project addresses the research questions as well as the domains on which the research builds, the novelty offered by the research, and how the research is validated. Different studies were conducted during the PhD project. Articles I (Köhler and Pizzol 2019) and III (Pizzol et al. 2021) address the research gaps regarding determining the environmental impact of Bitcoin mining. Article I is the first reproducible LCA of the Bitcoin mining network that includes the identification of hotspots as well as sensitivity and uncertainty analyses. Article III investigates the nonlinearity of upscaling Bitcoin mining as an emerging technology. Article II (Köhler and Pizzol 2020) shows how blockchain-based technologies can be implemented in supply chains, taking into account the heterogeneity of implementations and that blockchain technology is only one component in a system of technologies. Building on how blockchain-based technologies are implemented, Article IV (Köhler et al. 2021b) investigates how such implementations can create positive social and environmental impacts, drawing from experiences from real cases. Finally, Article V (Köhler et al. 2021a) explores one of the mechanism to create an impact identified in Article IV – (voluntary) market mechanisms. As blockchain-based technologies have been proposed as an alternative mechanism to govern supply chain sustainability, Article V analyzes their relationship to voluntary sustainability standards, which are established mechanisms governing supply chain sustainability. Thereby, Articles II, IV, and V address the gaps identified in previous research on blockchain-based technologies in sustainable supply chains. Collectively, all five articles can be used to address the overarching research question and hypothesis.

Table 3: Academic articles that address the research questions as well as the research domain, the results' novelty, and their validity.

Research questions	**Academic article**	**Scientific domain**	**Novelty**	**Validity**
1. What is the environmental impact of (PoW) blockchain technology from a life cycle perspective based on the example of Bitcoin?	Article I: Life Cycle Assessment of Bitcoin Mining Article III: Nonlinearity in the life cycle assessment of scalable and emerging technologies	Life cycle assessment	- First reproducible LCA of the entire mining network - Including different phases of the life cycle of Bitcoin mining - Including more environmental impacts - Allowing the identification of hotspots - Including sensitivity and uncertainty analyses - Discussion of the nonlinearity of mining	- Use of established methodology (LCA) and databases - Contribution and sensitivity analyses - Comparison with other studies

2. How can blockchain-based technologies foster sustainability based on the example of applications in supply chains?	Article II: Technology assessment of blockchain-based technologies in the supply chain	Technology assessment, case study research	- Assessment of how blockchain-based technologies can be implemented, showing the heterogeneity of cases - Blockchain-based technologies are a system of technologies, not a stand-alone technology - Blockchain-based technologies may bring positive impacts, but impacts depend on system design	- Confirmation of the findings by several cases - Accessible case study database of individual and cross-case analysis - Use of a technology assessment framework based on literature
	Article IV: Unfinished roads – blockchain to sustainability in supply chains	Grounded theory, supply chain management	- In-depth analysis of how blockchain-based technologies in supply chains can have positive social and environmental impacts - Identification and description of specific impact pathways and mechanisms - Interviews with experts who have experience with cases that have involved real implementation incl. different actors (technology provider, supplier, brands, etc.)	- Testing of interview protocol - Use of established methodology (grounded theory) - Inclusion of experts with different positions and from different countries
	Article V: Sustainability standards and blockchain in agro-food supply chains: Synergies and conflicts	Case study research, supply chain governance	- First assessment of the relationship and interaction with voluntary sustainability standards - Identification of different relationships (co-existing, synergistic, antagonistic) and their characteristics showing the heterogeneity of blockchain-based technologies	- Use of assessment criteria based on literature - Accessible case study database incl. individual case, cross-case, and critical analysis

4. THEORIES AND METHODS

This section presents the theories and methods used to address the research questions. Section 4.1 introduces prospective technology assessment. The following sections then describe which methods and tools were used to conduct a prospective technology assessment of blockchain technology. Section 4.2 illustrates the need for a life cycle assessment framework within this PhD project and how the LCAs were modeled. Section 4.3 presents the case study research, and Section 4.4 shows how the grounded theory research was conducted.

4.1. PROSPECTIVE TECHNOLOGY ASSESSMENT

Technology assessment is the systematic identification, analysis, and evaluation of a technology. It can assist decision-makers by providing an objective analysis of the consequences of a technology and help avoid the unwanted side-effects of new technologies (Van Eijndhoven 1997). However, it is not easy to predict the future effects of technology. The Collingridge dilemma explains that technology assessment has severe limitations as an early warning system, as at different stages of technology development either the knowledge or the power to make changes to the technology is missing. It states:

> *''The social consequences of a technology cannot be predicted early in the life of the technology. By the time undesirable consequences are discovered, however, the technology is often so much part of the whole economics and social fabric that its control is extremely difficult. This is the dilemma of control. When change is easy, the need for it cannot be foreseen; when the need for change is apparent, change has become expensive, difficult and time consuming.''* (Collingridge 1980)

As the world is facing challenges due to rapid technological change, the recognition that technology could have unanticipated consequences has grown. Many of those challenges are also closely related to environmentalism and concerns about industrial pollution, the disruption of communities, and undesirable outcomes of technology (Coates et al. 2001). Technology assessment is one tool that can be used to address these challenges; however, it has been noted that technology assessments focus solely on technical aspects, and technology is only one part of the solution to these issues (Coates 2001).

Therefore, Liebert and Schmidt (2010) suggested prospective technology assessment as an extension of and supplement to established technology assessment concepts. The idea here is to better adapt to the age of technoscience, referring to the recent transformation of science, technology, and innovation systems. There is no longer a clearly defined line between science and technology because science is everywhere (Liebert and Schmidt 2010). Many different actors are involved in shaping technology, as unbiased experts no longer exist (Liebert and Schmidt 2010). Prospective technology assessment is described as particularly interesting when long periods of development before technology maturity are required. The new concept of prospective technology assessment focuses on three requirements (Liebert and Schmidt 2010):

1. Early-stage orientation
2. Intention and potential orientation
3. Shaping orientation

Early-stage orientation is considered important to tackling problems of path dependency and entrenchment (Liebert and Schmidt 2010). In the early stages of development, it is still comparatively easy to make changes to a technology and address potential unwanted consequences, although it is also difficult to know what these are.

Intention and potential orientation can be one way of addressing this difficulty. In many cases, the intentions, goals, and objectives of an implementation can be determined (Liebert and Schmidt 2010). There is much we can learn about a technology at the beginning of its development by examining the intentions, goals, and objectives behind it. It may be possible to identify negative side effects and risks early by conducting a systematic analysis of technoscientific potentials and intentions, which includes uncertainties and risks, foreseeable impacts and undesired consequences, underlying values of actors, constellations of interests, and conflicting value frameworks (Liebert and Schmidt 2010). Deliberate discussions about these factors may already take place. Thus, analyzing intentions and potentials can be a key element in prospective technology assessment.

Shaping orientation is another important element. Scientific goals and procedures are intertwined with social and economic purposes that are external to science. The boundaries between these become blurred (Liebert and Schmidt 2010). Heterogeneous actors on various levels – not just the developers – shape the whole innovation process. For example, society is involved in how it reacts to and demands change, while the government plays an important role in how it regulates technology and development. Conflicting interests affect the shaping process for future technologies that stem from different approaches, interests, and priorities from and within the research community, national policies, environmental organizations, public opinion, companies, etc. (Liebert and Schmidt 2010). Coates and Coates (2016) highlight the importance of incorporating different perspectives to increase inclusivity during the process of shaping a technology.

In the case of blockchain technology, where potentials for both environmental damage and sustainability advancements were already identified in the early stages, it is important to investigate potential trade-offs arising from technology adoption. If concerns about environmental impacts related to cryptocurrency mining are as substantial as claimed, early-stage interventions can be valuable in order to prevent technology lock-in. The goals and intentions of different blockchain projects should be considered, as not every project is the same, and system design can have a major impact. Finally, it is important to acknowledge that the technology-shaping process is influenced by not just the immediate technology developers but also a variety of other actors, including members of academia.

Both quantitative and qualitative methods have been used in technology assessments (Coates et al. 2001). This PhD project, thus, adopts a mixed-methods approach to assess different blockchain implementations. Life cycle assessment (LCA) has been identified as a tool to support the identification of environmental improvement potentials in the early development stages (Hetherington et al. 2014). In particular, prospective LCA can be employed early in technology development when major alterations are still possible to provide guidance from an environmental perspective (Arvidsson et al. 2017). Thus, to address the first research question, theories and methods from the domain of LCA were applied as a quantitative approach for environmental assessment (Ekvall and Weidema 2004; Suh and Yang

2014). Qualitative research can also be suitable for prospective technology assessment, as it is conducted when a phenomenon needs to be explored but the data is unavailable or not easily measured (Creswell and Poth 2018). As blockchain technologies are still in the early stages and only scarce data is available, qualitative research can be used to explore specific cases and experiences. The second research question is addressed using a qualitative approach, as research on blockchain-based technologies in sustainable supply chains is still emerging and explorative qualitative studies are a suitable tool to investigate current research gaps (Lim et al. 2021). In this PhD project, two case study-based analyses were conducted along with one grounded theory-based study using interviews with stakeholders.

4.2. LIFE CYCLE ASSESSMENT

LCA is a quantitative framework used to assess environmental impacts associated with the different life phases of a product or service. This life cycle perspective is particularly useful when examining product systems that involve environmental impacts occurring during different phases. For example, the energy produced from fossil fuels typically has high impacts during the use phase, while energy produced from renewable sources often has higher impacts during the manufacturing phase (Asdrubali et al. 2015).

Two main approaches to LCA exist, namely attributional LCA and consequential LCA. In attributional LCA, a share of the potential global environmental impacts is attributed to a product life cycle (Schaubroeck et al. 2021). Attributional LCA can, therefore, be used to assess environmental impacts that have occurred during the production of a product. Consequential LCA describes the environmental consequences of a decision (Schaubroeck et al. 2021). Therefore, consequential LCA can be used to assess environmental impacts related to a change in the demand for a product or service. It can also be used for prospective technology assessment, analyzing the environmental impact associated with the increasing demand for an emerging technology.

While there is substantial potential for identifying and implementing environmental improvement opportunities using LCAs of emerging technologies, assessing the environmental impact of early-stage technologies also brings challenges (Hetherington et al. 2014). Early in the development stages, there is little primary data available, and secondary and proxy data must additionally be used (Hetherington et al. 2014). LCAs on emerging technologies are also faced with high uncertainty which must be addressed in the models (Hetherington et al. 2014). Additionally, there are problems with comparability, which exist for conventional LCA, too, but are even more dominant in LCAs of early-stage technologies, as less is known about an emerging technology (Thonemann et al. 2020). Finally, scaling issues exist, as it is unclear if and how many of the environmental impacts will decrease throughout the development process (Hetherington et al. 2014).

LCA was identified as a suitable approach to address the existing gaps in research on the environmental impacts of Bitcoin mining. While several studies estimate the carbon footprint of Bitcoin mining, LCA can provide an established framework to not only assess the carbon footprint but also include other environmental impacts. Additionally, the introduction of LCA adds a life cycle perspective, while all previous studies focused on the use phase only. Including other phases, such as manufacturing, provides a more holistic picture of the impacts and prevents the omission of impacts that do not occur in the use phase. Finally, a LCA can allow a hotspot analysis and facilitate the modeling of different scenarios to address the data scarcity on mining locations.

This PhD project took both a retrospective and a prospective approach to LCA, and two different system models were used. The retrospective analysis was conducted using attributional LCA, while the prospective analysis used consequential LCA (Weidema 2018). The attributional model was employed to determine the historical environmental impacts from Bitcoin mining for the 2018 to mid-2021 period, whereas the consequential LCA was employed to estimate the environmental consequences of an increase in Bitcoin mining. The LCA models enable the identification of impact hotspots. Those were analyzed and suggestions for improvements were explored. More details on the methods and materials used for the LCA of Bitcoin mining can be found in Articles I and III (Köhler and Pizzol 2019; Pizzol et al. 2021). For this PhD thesis, the original study was updated to include historical assessments from 2018 until June 2021. Relevant new information for the update is described in the subsequent paragraphs.

One key adaptation from the 2018 model is the geographical distribution of miners, which has since changed. Table 4 shows the different geographical distributions for the attributional models adjusted to different time periods. The 2018 data is taken from Article I. The 2019 and 2020 data are taken from the mining map of the CBECI (Cambridge Centre for Alternative Finance 2020). It should be noted that the data for 2019 may underestimate the miners in Xinjiang and overestimate those in Sichuan as miners in China migrate between the two regions due to wet and dry seasons (de Vries 2019). The opposite may be true for the 2020 data. Due to a lack of data for the first half of 2021, the 2020 data were used for this period as well.

Table 4: Geographical distribution of Bitcoin mining for the attributional models from 2018 to 2020 (all locations contributing over 1% are included and then scaled to 100%)

Location	2018	2019	2020
China	53.5%	78.7%	73.0%
Sichuan	30.5%	30.2%	12.1%
Inner Mongolia	12.3%	8.1%	9.4%
Xinjiang	10.7%	27.1%	41.4%
Yunnan	-	9.5%	6.6%
Gansu	-	2.5%	1.7%
Beijing	-	1.3%	1.8%
Canada	12.8%	-	-
Alberta	4.7%	-	-
British Columbia	4.1%	-	-
Quebec	4.0%	-	-
USA	13.7%	5.7%	6.3%
New York state	7.5%	-	-
Washington state	6.2%	-	-
Iceland	4%	-	-
Georgia	4%	-	-
Norway	4%	-	-
Sweden	4%	-	-
Russia	4%	6.9%	6.9%
Malaysia	-	4.0%	4.7%
Iran	-	2.2%	3.8%
Kazakhstan	-	1.9%	5.2%

The other parameter that was adapted for the updated models is the energy demand of the mining equipment employed in the Bitcoin mining network. While it is not possible to know the exact machines used for mining due to different conditions across the mining network (e.g. electricity prices in different locations) and continuous changes in profitability with the volatile Bitcoin market price, sales numbers and historical efficiency improvement represent valuable information. Based on this information, the efficiency of the mining equipment in the models was assumed to be 94.0 watt/TH/s for 2018, 76.8 watt/TH/s for 2019, 61.5 watt/TH/s for 2020, and 49.2 watt/TH/s for the first half of 2021. The 2018 and 2019 data are based on reports from CoinShares (Bendiksen et al. 2018; Gibbons and Bendiksen 2019). The efficiencies for 2020 and 2021 assume a 20% improvement, in line with the development of the previous years.

While the retrospective model can be adapted to analyze different historical periods, the consequential approach is fundamentally different, as it focuses on quantifying the effect of an increase in the demand for mining. The prospective models explore the nonlinear effects of expanding the Bitcoin mining network, including the structural changes of the product system itself. The system does not scale linearly, which is mainly due to two factors: the new mining equipment employed is more energy efficient than the average equipment of previous years, and new mining capacity is not installed proportionally in all existing mining location and is even installed in new locations (Pizzol et al. 2021). To address this upscaling issue, a consequential approach was adopted in an attempt to gain insights into the upscaling of the Bitcoin mining network for early 2019 and 2020. The upscaling scenarios consider changes in the locations of miners and the energy efficiencies of the mining equipment.

Four different scenarios were modeled: a business-as-usual (BAU) scenario, a location-sensitive scenario, a technology-sensitive scenario, and a technology-and-location-sensitive scenario. In the BAU scenario, the geographical distribution of the miners is irresponsive to the change in the demand for mining. However, the energy system and electricity network are responsive to changes in the overall demand for electricity. The BAU scenario shows linear growth and can be taken as a reference against which the other scenarios are compared. In the location-sensitive scenario, an increase in demand will only be met by adding new mining capacities under more competitive conditions (e.g. lower energy prices). For example, for 2019, it was projected that new mining facilities would open in Scandinavia, North America, and Russia (Köhler and Pizzol 2019). For 2020, the projections were different, whereby new mining capacity was proposed to open in Xinjiang, Inner Mongolia, Malaysia, Iran, and Kazakhstan (Pizzol et al. 2021). In the technology-sensitive scenario, an increase in demand for mining will only be met by the most efficient mining equipment. The technology-and-location-sensitive scenario combines scenarios two and three.

LCAs work with models. As with all models, they do not capture every detail of reality. The uncertainty related to the models should therefore be taken into consideration. For Bitcoin mining, this is specifically important, as parameters change constantly. Miners open new facilities, old equipment is used in high-price periods and then shut off again, and new equipment replaces older equipment. The system is in continuous change. In order to address this uncertainty, several steps were taken.

First, the uncertainty related to the ecoinvent background data was assessed by running 1,000 iterations of Monte Carlo simulations (Groenenberg et al. 2010; Mendoza Beltran et al. 2018). The second issue that was addressed involved the scarce and uncertain information on mining locations. To help resolve this issue, six different scenarios of the electricity mix were modeled (Köhler and Pizzol 2019). Finally, the sensitivity of the baseline model related to mining efficiency and equipment lifetime was investigated (Köhler and Pizzol 2019).

The analyses were conducted using the Brightway2 open source LCA software (Mutel 2017) and can be reproduced (Köhler and Pizzol 2019; Pizzol et al. 2021). Results for the 2019, 2020, and 2021 additions can be reproduced using the code available in a GitHub repository (Köhler 2021).

4.3. CASE STUDY RESEARCH

Case study research is a qualitative approach in which the researchers investigate a real-life contemporary bounded case or multiple cases using various sources of data (Creswell and Poth 2018). Two of the three studies addressing Research Question 2 – *How can blockchain-based technologies foster sustainability based on the example of applications in supply chains?* – took this approach. One study (Article II) investigated how blockchain-based technologies can be implemented in food supply chains by examining how the technologies have been implemented in several cases (Köhler and Pizzol 2020). The other study (Article V) analyzed how blockchain-based technologies and voluntary sustainability standards interact with each other in relation to the governance of agro-food supply chain sustainability, assessing different blockchain-based technology and voluntary sustainability cases (Köhler et al. 2021a). For both studies, a case study approach was useful to evaluate real cases, determine what has been implemented thus far, and explore what can be observed. Since most of the literature focuses on the potentials of blockchain technologies, we wanted to explore what their current state was and what experiences actual implementation had already made.

The research process consisted of four to five steps: case selection, assessment framework definition, individual case analysis, cross-case analysis, and, in the case of Article V, critical assessment (Köhler and Pizzol 2020; Köhler et al. 2021a).

The *case selection* stands at the beginning of case study research. Selection criteria are chosen to define the cases within certain parameters (Creswell and Poth 2018). In both studies, multiple cases were selected to provide insights on the variety of different cases within the defined parameters. The selection criteria allowed the scope to be narrowed while at the same time increasing comparability. Multiple cases enable comparisons, leading to the identification of otherwise inaccessible conclusions (Creswell and Poth 2018). Analyzing multiple cases made sense in both studies because it helped to address the research questions. For example, Article II investigates how blockchain-based technologies can be implemented (Köhler and Pizzol 2020). Naturally, multiple cases were needed to provide insight into different system designs. Article V analyzes the interaction between blockchain-based technologies and voluntary sustainability standards (Köhler et al. 2021a). This study needed to include multiple cases that could indicate whether more than one type of interaction existed and, if so, how the different relationships could be characterized. In both studies, the cases were identified using a mixture of web searching, networking with stakeholders inside the blockchain community, subscriptions to different newsletters, and searching the database PositiveBlockchain.io (PositiveBlockchain 2019; Köhler and Pizzol 2020; Köhler et al. 2021a).

Second, *assessment frameworks* were defined. For Article II, a technology assessment based on literature was used (Müller 2011;

Köhler and Pizzol 2020). The technology assessment framework states that any technology is made up of four components: knowledge, organization, technique, and product. A change to any one of these four components will lead to changes in the others, as they are closely connected. In Article V, the cases were assessed against twelve sustainability-related criteria. These criteria were defined based on existing literature (Astill et al. 2019; Kamilaris et al. 2019; Mahyuni et al. 2020; Katsikouli et al. 2021) and refined after a first round of case analysis (Köhler et al. 2021a). Both of these assessment frameworks were chosen so that the research questions could be addressed.

Next, the *individual cases* were analyzed based on the respective assessment frameworks. In Article II, the cases were analyzed according to the four components of the technology assessment framework (Köhler and Pizzol 2020). In Article V, both the blockchain-based technology and the voluntary sustainability standard cases were assessed against the twelve assessment criteria (Köhler et al. 2021a).

After the individual case analysis, a *cross-case analysis* was conducted. In Article II, the results from the different cases were compared for each technology component. For example, it was determined which of the different technologies were used across all cases, but also which were used in only a few cases or even a single case (Köhler and Pizzol 2020). For this study, the cross-case analysis was the final step, as it addressed the research question of how blockchain-based technologies are implemented in the supply chain. For Article V, the blockchain-based cases were compared to each other before the voluntary sustainability cases were compared to each other; these comparisons were conducted to identify cross-cutting patterns within each of the two types of cases. Afterward, the blockchain-based technology cases were compared to the voluntary sustainability cases, showing the similarities and differences as well as the strengths and weaknesses of both types (Köhler et al. 2021a).

Finally, a *critical assessment* was carried out for Article V. Based on the individual and cross-case analyses, the relationship between blockchain-based technology cases and voluntary sustainability cases was assessed (Köhler et al. 2021a). This additional step was necessary to address the research question and investigate how blockchain-based technologies and voluntary sustainability standards interact.

4.4. GROUNDED THEORY

Grounded theory is a qualitative research approach that seeks to generate a general explanation of a process, an action, or an interaction (Creswell and Poth 2018). The explanation should be grounded in data and arise from the perspectives of relevant individuals. Interviews can be a suitable data collection method. Article IV aimed to discover the mechanisms by which blockchain-based technologies in supply chains generate positive social and environmental impacts (Köhler et al. 2021b). An explorative approach using expert interviews was considered suitable because no previous research existed on how blockchain-based technologies in supply chains create impacts (Köhler et al. 2021b).

Blockchain-based technologies are still emerging, their applications are in the early stages of development, and their impacts are not yet fully known. Since a conclusive explanatory theory of how blockchain-based technologies positively impact supply chains is currently out of reach, Article IV proposed a middle-range theory instead (Craighead et al. 2016). Such a theory is context-specific and should further be tested as the technology matures.

The research process can be divided into three parts: participant sampling, interview procedure, and interview analysis.

Both theoretical and snowball *sampling* were used. Theoretical sampling refers to a sampling approach wherein participants are chosen based on leads in the data (Reilly et al. 2012). It is an iterative process, with new participants identified based on previous interviews (Tie et al. 2019). Individuals who had first-hand experience with implementing blockchain-based technologies in supply chains were selected for Article IV (Köhler et al. 2021b). Snowball sampling was also applied. At the end of each interview, participants could suggest other suitable individuals, as they are well connected within the field.

In-depth, semi-structured *interviews* were conducted for Article IV to retrieve detailed information about blockchain-based technology implementations and the factors shaping these implementations (Köhler et al. 2021b). While an interview guide with specific questions was prepared, a semi-structured interview approach provided the freedom to adjust to specific participants and their knowledge. The participants were invited to join via e-mail, and when they agreed, a call was scheduled. Typically, the interviews lasted between 30 and 45 minutes (Köhler et al. 2021b).

The interviews were transcribed and anonymized before the *analysis*. Then, a qualitative content analysis was conducted to identify common themes. The process was iterative, including several coding rounds with new interviews. The process was continued until no new themes were found. A set of themes could then be grouped into dimensions that are shown in a final scheme (Köhler et al. 2021b).

5. RESULTS: GAME CHANGER OR CLIMATE KILLER?

This section provides an overview of the energy consumption and environmental footprint of Bitcoin mining. Section 5.1 presents the energy consumption and impacts for the years 2018, 2019, 2020, and January-June 2021. Section 5.2 outlines a hotspot analysis of these results. In Section 5.3, the results of the sensitivity analysis are presented. Finally, Section 5.4. outlines the environmental impact of increasing the energy demand of Bitcoin mining by 1 TH and provides an idea of future impacts.

5.1. ATTRIBUTIONAL MODEL

The attributional model shows the historic energy consumption and carbon footprint of Bitcoin mining for the 2018 to mid-2021 period. The results of the baseline model can be found in Table 5. The results for 2018 are taken from Köhler and Pizzol (2019). The results for 2019 to mid-2021 have been updated using new data (Cambridge Centre for Alternative Finance 2020) for the mining locations. The data regarding the energy efficiency of the mining equipment were obtained from Gibbons and Bendiksen (2019) for 2019. For 2020 and January-June 2021, a 20% annual improvement in efficiency was assumed based on historical data (Köhler et al. 2021a, b).

Table 5: Energy consumption and carbon footprint for 2018, 2019, 2020, and January-June 2021, plus the carbon footprint per TH for each year

year	Energy consumption [TWh]	Energy consumption per TH [mWh/TH)	Carbon footprint [MtCO$_2$-eq]	Carbon footprint per TH [mgCO$_2$-eq]
2018	31.29	27.14	17.30	15
2019	48.90	23.47	32.98	15.8
2020	70.65	18.78	58.79	15.6
mid-2021	72.00	15.02	60.07	12.5

The results of the energy consumption of Bitcoin mining shown in Table 6 are consistent with previous studies (2018: 40-62 TWh/yr de Vries (2019), 45.8 TWh/yr Stoll et al. (2019), 62.5 TWh/yr Digiconomist (2021), 41.8 TWh/yr CBECI (2021); 2019: 87.1 TWh/yr de Vries (2020), 64 TWh/yr Digiconomist (2021), 54.5 TWh/yr CBECI

(2021); 2020: 70.4 TWh/yr Digiconomist (2021), 70.4 TWh/yr CBECI (2021); 2021: 184 TWh/yr de Vries (2021)).

While the results are at the lower end of this range for 2018 and 2019, the 2020 result is higher than the Bitcoin energy consumption indices of Digiconomist and Cambridge University. This is mainly due to varying assumptions across the different studies. Other studies conduct their calculations based on the hashrate on a given day rather than taking the average for a longer time frame (de Vries 2018, 2021; Stoll et al. 2019), so the studies do not precisely compare the same period. De Vries and Digiconomist also take the economic approach for their calculations. Deviations with CBECI depend on the efficiency assumed for the mining hardware.

The results regarding the carbon footprint of Bitcoin mining are also in line with those of previous studies (2016-mid 2018: 3-13 Krause and Tolaymat (2018); 2018: 22-22.9 $MtCO_2$-eq Stoll et al. (2019), 19-29.6 $MtCO_2$-eq de Vries (2019); 2021: 90.2 $MtCO_2$-eq de Vries (2021)). Deviations are in part due to the divergent energy consumption calculations. Furthermore, the methods used to calculate the carbon footprint differ. Both Stoll et al. (2019) and de Vries (2019) use average

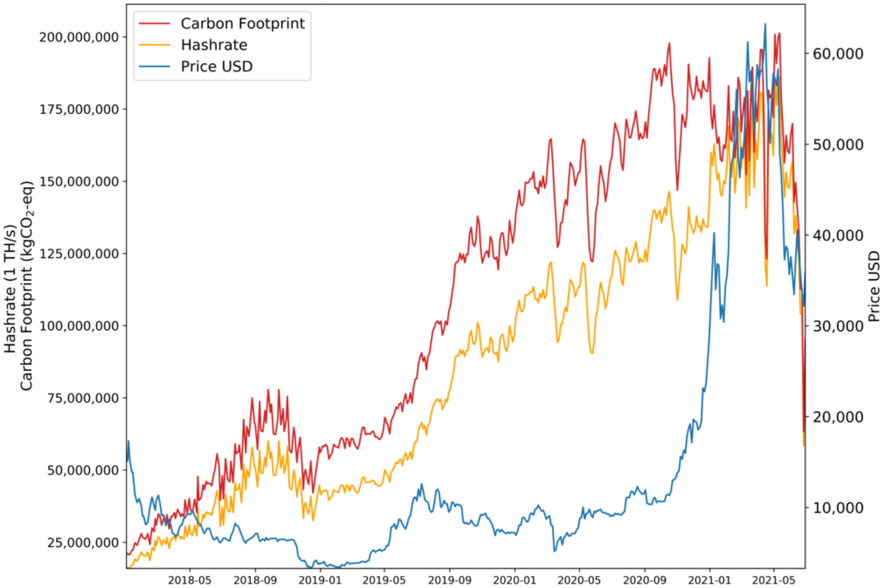

Figure 3: Carbon footprint of Bitcoin mining from 2018 to mid-2021

emission factors for produced electricity in each country and associate it with the share of electricity consumption for mining in that region. For 2021, the results of this study are higher than those of de Vries (2021). This is mainly because the model in this thesis assumes a high share of miners located in Xinjiang.

Figure 3 displays the carbon footprint of the Bitcoin network from 2018 to mid-2021 together with the hashrate and the Bitcoin price in USD. The curves for the hashrate and the carbon footprint are directly proportional for each year, as all parameters except the hashrate remain constant throughout each year. For 2021, severe dips and highs can be observed. These are due to external factors, such as Tesla buying $1.5 billion worth of Bitcoin, announcing they would accept vehicle payments in Bitcoin, and then suspending the payments again (de Vries et al. 2021; Reisch et al. 2021).

Table 6 displays the results for computing 1 TH from 2018 to mid-2021 for all the midpoint impact categories considered in this study. Ours is the only study we are aware of that quantitatively assesses environmental impacts beyond the carbon footprint.

Table 6: Environmental impacts of 1 TH in retrospective model for 2018, 2019, 2020, and January-June 2021 according to the IPCC and the ReCiPe methods (adapted and updated from Köhler and Pizzol 2019)

Impact Category	2018	2019	2020	Jan–Jun 2021
climate change GWP (mgCO_2-eq), IPCC	15.0	15.8	15.6	12.5
climate change GWP (mgCO_2-eq), ReCiPe	14.7	15.4	15.3	12.3
fossil depletion FDP (MJ)	3.74E-06	3.91E-06	3.86E-06	3.09E-06
metal depletion MDP (kg)	3.36E-07	2.60E-07	2.54E-07	2.27E-07
human toxicity HTP (kg 1,4-DCB-eq)	5.65E-06	4.13E-06	4.14E-06	3.43E-06
terrestrial acidification (kg SO_2-eq)	6.04E-08	6.86E-08	6.89E-08	5.53E-08
freshwater eutrophication (kg P-eq)	6.59E-09	4.17E-09	4.07E-09	3.32E-09
photochemical oxidation formation POFP (kg ethylene-eq)	4.24E-08	4.74E-08	4.69E-08	3.76E-08
ozone depletion ODP (kg CFC-11-eq)	4.74E-13	3.53E-13	3.38E-13	2.73E-13
terrestrial ecotoxicity (kg 1,4-DCB-eq)	7.16E-10	6.64E-10	6.66E-10	5.41E-10
marine ecotoxicity (kg 1,4-DCB-eq)	3.06E-07	1.76E-07	2.54E-07	1.46E-07
freshwater ecotoxicity (kg 1,4-DCB-eq)	3.43E-07	1.95E-07	1.97E-07	1.61E-07

5.2. HOTSPOT ANALYSIS

We conducted a contribution analysis for the 2018 attributional model showing the impact hotspots of Bitcoin mining with a focus on the carbon footprint. We specifically addressed the life cycle phases, mining locations, and types of equipment used.

The use phase was identified as the major contributor to the carbon footprint. 99.04% of the carbon footprint can be associated with this phase. The equipment production and EoL phases only contributed 0.93% and 0.03% to the carbon footprint, respectively (Köhler and Pizzol 2019).

Figure 4 provides an overview of each identified location's share in mining and contribution to Bitcoin's carbon footprint for 2018. Four locations (Inner Mongolia, Xinjiang, Alberta, and Russia) alone contributed more than 70% of the total carbon footprint of Bitcoin mining. The figure also shows that for these locations, the carbon footprint is larger than the share in mining, meaning that the carbon intensity of the electricity used in these locations is higher than the average carbon intensity in this model. Locations such as Quebec, Iceland, and Sichuan contribute little to the total carbon footprint. The electricity mixes in these regions are less carbon-intensive than the

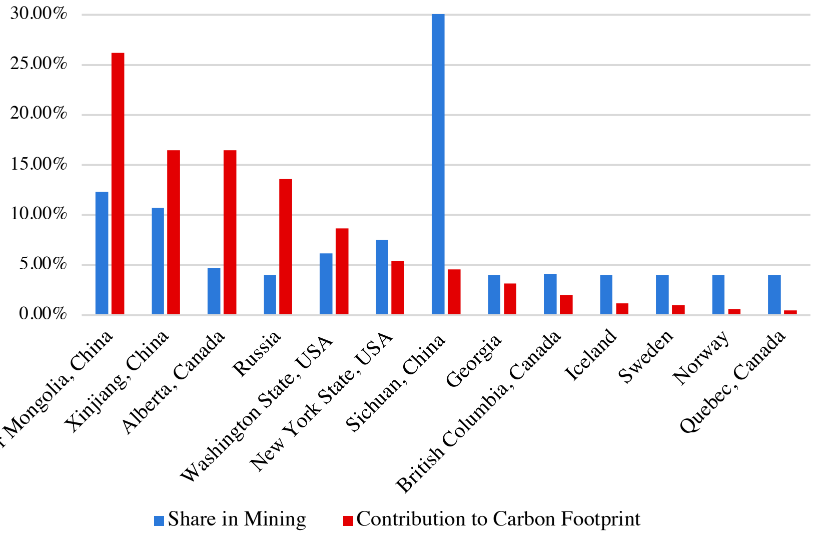

Figure 4: Mining location hotspots (based on Köhler and Pizzol 2019)

average in this model. This indicates that when new mining facilities open in these regions, rather than in locations such as Inner Mongolia, the carbon footprint per TH decreases.

5.3. SENSITIVITY ANALYSIS

An analysis of the sensitivity of different model parameters was also conducted. Specifically, the parameters of miner location, electricity consumption of the mining equipment, hashrate of the mining equipment, and lifetime of the mining equipment were analyzed.

Figure 5 shows that the effect of the electricity mix on the carbon footprint is substantial. Using only electricity from coal or only electricity from hydropower results in the upper and lower bounds, respectively. The global electricity mix offers a comparison between the carbon intensity of the electricity used for Bitcoin mining and all the electricity consumed worldwide.

Figure 5 shows the results from modeling the worst-case scenario, the best-case scenario, and a global average electricity mix scenario as well as three different geographical distributions of miners: one based on mining pool data, one based on a study by the Cambridge Centre for Alternative Finance (CCAF; Rauchs et al. 2018), and one based on a

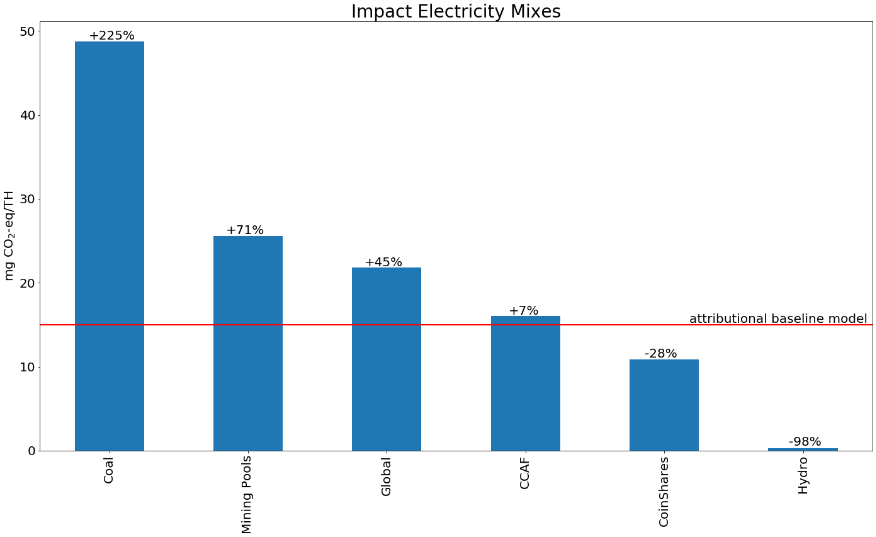

Figure 5: Sensitivity of the electricity mixes and mining locations in the 2018 attributional model (reproduced from Köhler and Pizzol 2019)

CoinShares report (Bendiksen et al. 2018). These are compared to the attributional baseline model for 2018. The main differences in results of these scenarios involve the mining locations in China. The CoinShares scenario includes a large share of miners in Sichuan, where 77% of the electricity is produced from hydropower (Köhler and Pizzol 2019). For the Mining Pool scenario, only country-wide data were available, highlighting the importance of obtaining specific data on mining locations. For example, producing 1MJ using the average Chinese electricity mix leads to 0.313 kg CO_2-eq, while producing 1MJ in Sichuan province only leads to 0.097 kg CO_2-eq (Köhler and Pizzol 2019).

The model indicates a high sensitivity to a change in electricity consumption. A 10% decrease or increase in electricity consumption leads to a decrease or increase of 9.9% in the carbon footprint, respectively (Köhler and Pizzol 2019). Similarly, the sensitivity to a change in the hashrate is high. A 10% decrease or increase in the hashrate leads to a 10% decrease or increase of the carbon footprint, respectively (Köhler and Pizzol 2019). These results highlight that the efficiency of mining equipment (electricity consumption per TH) has a strong influence on the carbon footprint per TH. It should be noted that the hashrate also has a substantial influence on the carbon footprint of Bitcoin mining.

It was further found that a decrease in the lifetime of the mining equipment from 1.5 years to 1 year only resulted in a small 0.48% increase in the carbon footprint (Köhler and Pizzol 2019). Similarly, an increase to 2 years led to a minor decrease of 0.24 % (Köhler and Pizzol 2019). Since the production phase contributes less than 1% to the overall carbon footprint, the effect of the lifetime of the mining equipment is negligible (Köhler and Pizzol 2019).

We can thus conclude that the major impact drivers of Bitcoin mining are mining location (and the associated electricity mix used), the energy efficiency of the hardware (watt/TH mined), and the network's hashrate.

5.4. CONSEQUENTIAL MODEL AND FUTURE SCENARIOS

The consequential models investigated how the carbon footprint would change as the demand for computing hashes increased. Below, Table 7 shows the carbon footprint of mining one additional TH for all modeled scenarios.

The BAU scenario assumes a linear growth and serves as a baseline against which the other scenarios can be compared. It is not a realistic scenario; in reality, the expansion of the Bitcoin network will lead to changes in the geographical distribution of miners and improvements in mining efficiency. The technology scenarios for 2019 and 2020 can be observed to trigger a reduction of the per TH carbon footprint by 42% and 48%, respectively. However, in the location scenario, this is not the case. Under this scenario, the 2019 model leads to a 36% reduction in the carbon footprint, while the 2020 projection leads to an increase of 31%. This is mainly because for the 2019 projections, it was assumed that the miners would move to locations outside of China, such as Scandinavia or North America, which did not happen, according to the CBECI (Cambridge Centre for Alternative Finance 2020). The predictions for 2020 suggested an increased growth of miners within Chinese locations such as Xinjiang, where the electricity mix is carbon-intensive. The technology and location scenarios, i.e. the combined upscaling of both the geographical locations of miners and equipment efficiency, lead to a reduction compared to the BAU scenarios of 76% for 2019 and 32% for 2020. This is illustrated in Figure 6.

Table 7:Carbon footprint of mining one additional TH in all consequential scenarios for 2018 and 2019 (based on Köhler and Pizzol 2019; Pizzol et al. 2021)

Scenario	**climate change GWP (mgCO$_2$-eq), IPCC**
BAU Scenario (2019)	13.3
BAU Scenario (2020)	12.4
Location Scenario (2019)	(8.57)
Location Scenario (2020)	16.19
Technology Scenario (2019)	7.74
Technology Scenario (2020)	6.43
Technology and Location Scenario (2019)	3.20
Technology and Location Scenario (2020)	8.4

Based on historical information on the increased efficiency of mining equipment and the changing locations of miners, it can be assumed that over time, mining efficiency will continue to increase, and new

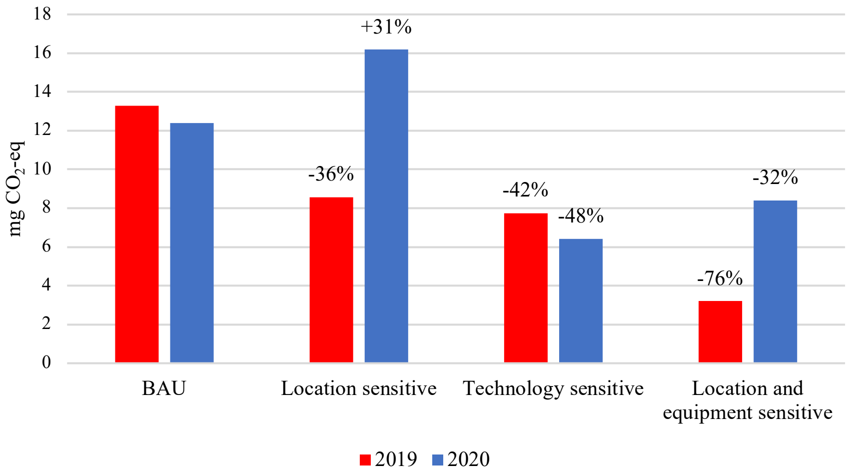

Figure 6: Carbon footprint in the consequential scenarios (based on Köhler and Pizzol 2019; Pizzol et al. 2021)

facilities will not be installed proportionally in all existing locations. A linear growth model (i.e. a BAU scenario) is therefore likely to be inaccurate.

It should be noted that these are only short-term scenarios, and they do not take outside shocks into account (Pizzol et al. 2021). Legislative changes, such as restricting certain locations (Alvarez 2018), would undoubtedly further impact the results. Considering that Bitcoin is still an emerging technology, unpredictable factors cannot be reliably forecasted. For the 2019 predictions, we assumed that China's crackdown on miners would influence the mining locations, which did not ultimately happen that year. Thus, the prospective scenarios always need to be considered in such a light. In the context of Bitcoin mining, long-term predictions may not be reasonable due to the speed and unpredictability of the mining network's changes. Therefore, the modeled scenarios are an exploration of potential future impacts and reflect a forecast of a short-term trend.

The varying results from the 2019 and 2020 projections suggest that it is especially important to obtain accurate data on mining facilities and the electricity mixes used for mining activities. They also reflect the need to build relevant scenarios for upscaling Bitcoin mining depending on the different scales and maturity levels of the technology (Pizzol et al. 2021). The results of the PhD project are limited to short-term projections.

6. RESULTS: REVOLUTIONIZING SUPPLY CHAINS?

This section provides an overview of the results from the studies addressing Research Question 2 and blockchain-based technologies in supply chains. Section 6.1 describes the results from Article II and how blockchain technology can be implemented in supply chains. Section 6.2 provides the results of Article IV and explains how blockchain-based technologies within supply chains can create positive social and environmental impacts. Finally, Section 6.3 summarizes the results of Article V and explains how blockchain-based technologies interact with voluntary sustainability standards and existing sustainability governance mechanisms in supply chains.

6.1. HOW BLOCKCHAIN-BASED TECHNOLOGIES CAN BE IMPLEMENTED IN SUPPLY CHAINS

The aim of Article II was to better understand the role of blockchain, build a foundation for further analyses, and further the discussion of the social and environmental implications of blockchain technology in supply chains. Section 4 introduced the technology assessment framework by Müller (2011), which stated that technologies consist of four components: technique, knowledge, organization, and product. In this section, the results for each of the four technology components are briefly summarized. More details can be found in Köhler and Pizzol (2020).

The *technique* component can be divided into several elements, including blockchain technology, tracking technology, data entry, data handling, data storage, data communication, and tokenized incentives (Köhler and Pizzol 2020). Figure 7 provides an overview of the different technologies that can be involved. The case study showed that blockchain-based technologies in the supply chain require several other technologies beyond blockchain and that various configurations of different elements are possible. The architecture design of such a blockchain-based technology system significantly affects the type of goal that can be achieved through its implementation. Each architectural choice carries trade-offs.

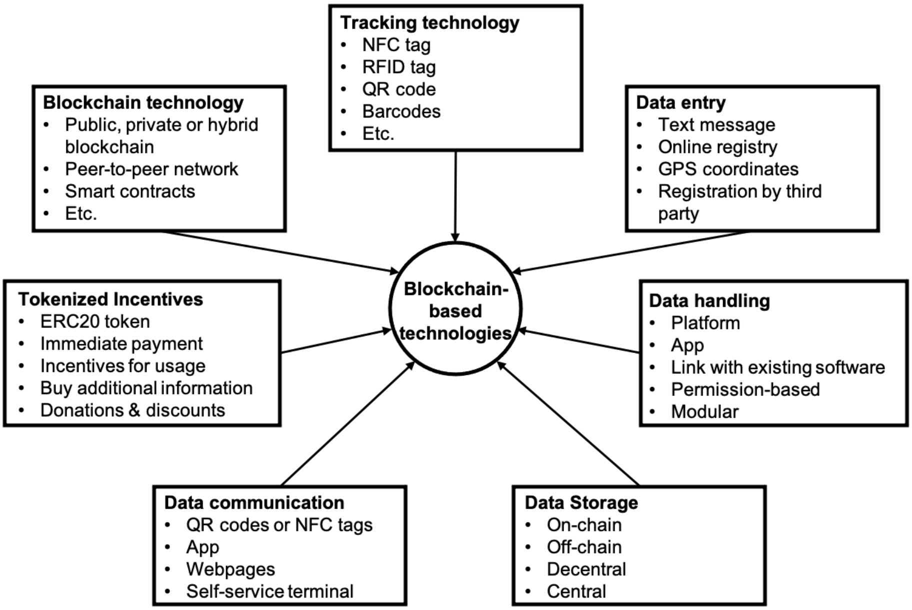

Figure 7: Overview of the technique components (reproduced from Köhler and Pizzol 2020)

Regarding the *knowledge* component, the study indicated that new knowledge is required for different actors, such as programmers, actors in the supply chain, and the public (Köhler and Pizzol 2020). Programmers need to acquire knowledge about blockchain architecture, off-chain storage options, smart contracts, communication with non-technical audiences, and in some cases new programming languages such as Solidity for applications on the Ethereum platform, to highlight just a few (Köhler and Pizzol 2020). Actors in the supply chain need to learn how to register, transfer, and update assets, how to connect the blockchain-based technology solution to existing software, and what to pay attention to when using blockchain-based technologies (Köhler and Pizzol 2020). The public needs to learn that QR-codes and NFT-tags lead to additional information on products; in cases where the blockchain is public, they also need to learn how to access and read blockchain data (Köhler and Pizzol 2020). This last point can be particularly important to creating additional public accountability.

The *organization* component demonstrates that many different stakeholders are involved. Figure 8 illustrates typical stakeholders involved in

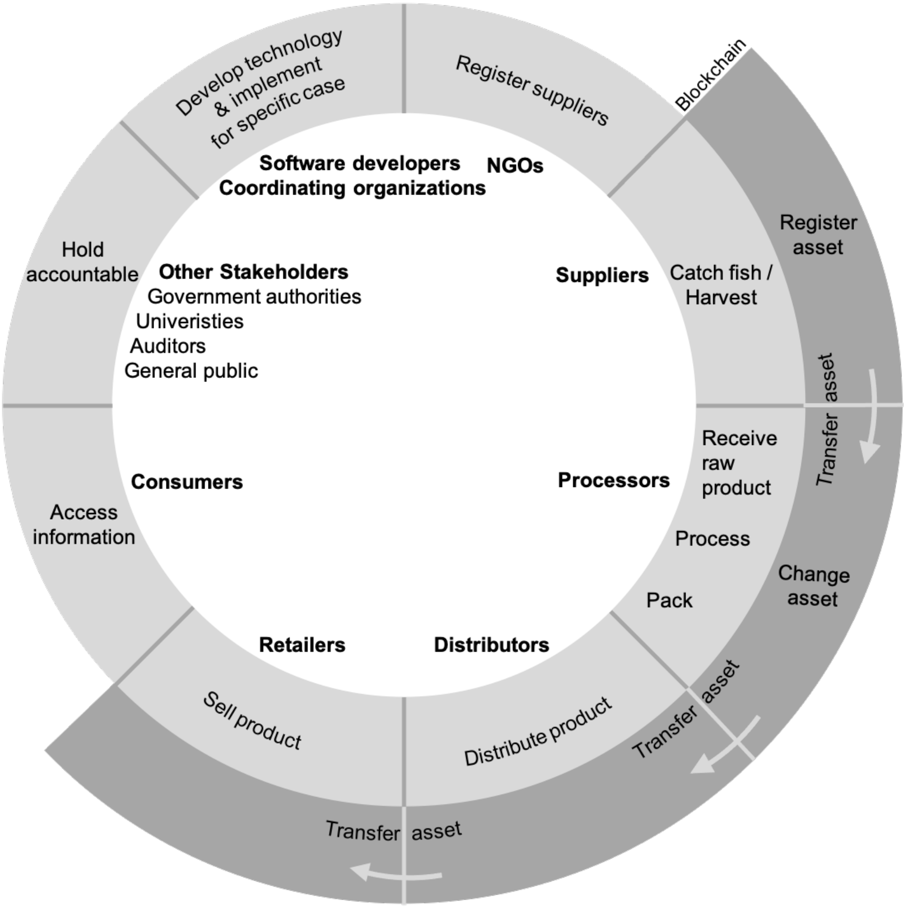

Figure 8: The stakeholders and their roles in a food supply chain implementing blockchain-based technologies (reproduced from Köhler and Pizzol 2020).

implementing blockchain-based technologies in food supply chains. In particular, the participation and coordination of the actors directly involved in the supply chain are necessary for implementing blockchain-based technologies in food supply chains. The architecture design (cf. technique component) also plays an important role regarding actor involvement. For example, role-based access can impact transparency and power dynamics. Additionally, public blockchains may allow external stakeholders to verify blockchain data and thus hold supply chain actors accountable (Köhler and Pizzol 2020).

The *product* component can be divided into three elements: consumer, company, and public (Köhler and Pizzol 2020). The consumer product refers to product-specific information such as provenance details. This information can typically be accessed through QR codes on the product (Köhler and Pizzol 2020). The company product refers to the management dashboard of the blockchain-based technologies implementation. It can provide access to product information in near-real-time (Köhler and Pizzol 2020). The product for the public refers to public blockchains that allow anyone to access blockchain data that they can then verify. This creates a higher level of transparency, as the information can be used for independent analyses and audits (Köhler and Pizzol 2020).

The analysis revealed that blockchain technology is not a stand-alone technology but rather part of a system of technologies (Köhler and Pizzol 2020). Blockchain-based technologies in supply chains are expected to have a variety of impacts. Some of these are expected to be direct impacts of using blockchain technology, including increased trust, traceability, transparency, and authenticity (Köhler and Pizzol 2020). Other impacts are considered to be more indirect. For example, improved data management is a side effect of digitizing non-digital processes (Köhler and Pizzol 2020). Additional impacts, such as increased sustainability, are expected to be induced by the use of blockchain-based technologies, but as of now no strong evidence exists (Köhler and Pizzol 2020). More long-term studies are needed to investigate these impacts.

6.2. HOW BLOCKCHAIN-BASED TECHNOLOGIES POSITIVELY IMPACT SUPPLY CHAINS

The findings of Article IV indicate that blockchain-based technology implementations in supply chains still remain in early stages of development (Köhler et al. 2021b). Most of the experts interviewed have already implemented their blockchain-based technologies, yet all of the experts are still improving their implementations (Köhler et al. 2021b).

Figure 9 shows the conceptual structures that were developed inductively from analyzing the interview data. The white boxes represent dimensions, which each include several themes. Detailed information about each theme can be found in the article (Köhler et al. 2021b). Within the conceptual structure, barriers and drivers represent pressures on the current system. Output refers to the implementations

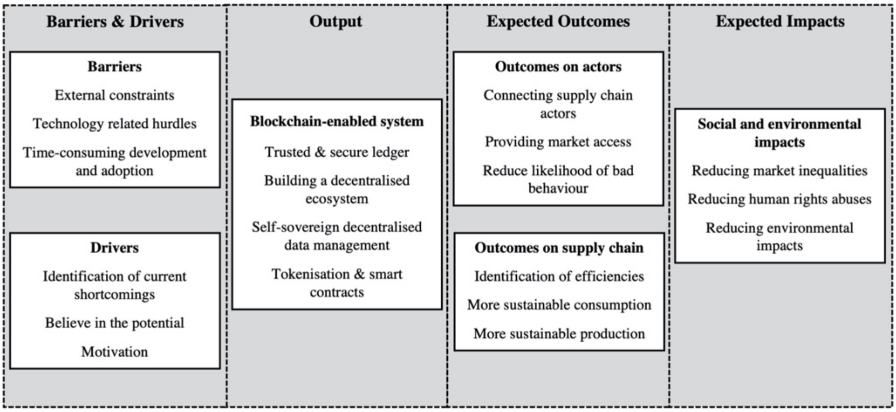

Figure 9: Conceptual structure explaining how blockchain-based technologies create positive social and environmental impacts (reproduced from Köhler et al. 2021b)

of blockchain-based technologies, which the study participants called blockchain-enabled systems. The expected outcomes are changes that directly resulted from the output, while the expected impacts are changes to human well-being and ecosystem well-being.

Based on the interview analysis and the conceptual framework, four mechanisms creating positive environmental and social impacts have been identified: (voluntary) market mechanisms, plausibility checks, smart contracts and tokenization, and peer-to-peer trust (Köhler et al. 2021b). These mechanisms are illustrated in Figure 10, which shows how the outputs in the first column influence the outcomes in the middle and how these outcomes, in turn, influence the resulting impacts in the last column. The arrows linking the outputs, outcomes, and impacts portray underlying impact pathways. Details on the mechanisms can be found in the article (Köhler et al. 2021b).

The findings did not allow a determination of whether the outcomes and impacts could be attributed to the blockchain component in the system. This may indeed not be possible, as many technologies are interlinked. The outcomes and impacts may instead be due to the implementation of the system of technologies, and it is not feasible to identify the contribution of each individual component (Köhler et al. 2021b). This result supports previous findings that the overall system design and integration are important for achieving positive social and environmental impacts, not just the inclusion of a single component.

The findings further show that study participants were unable to explain how they measure the impacts of their blockchain-based technologies implementation (Köhler et al. 2021b). While different participants expressed an interest in different measurements (e.g. increased income of farmers or reduced carbon emissions), it became clear that most projects lacked indicators for measuring impacts. This result is concerning, as it makes it difficult to evaluate the success of projects in relation to potential continuation, further development, or dissolution.

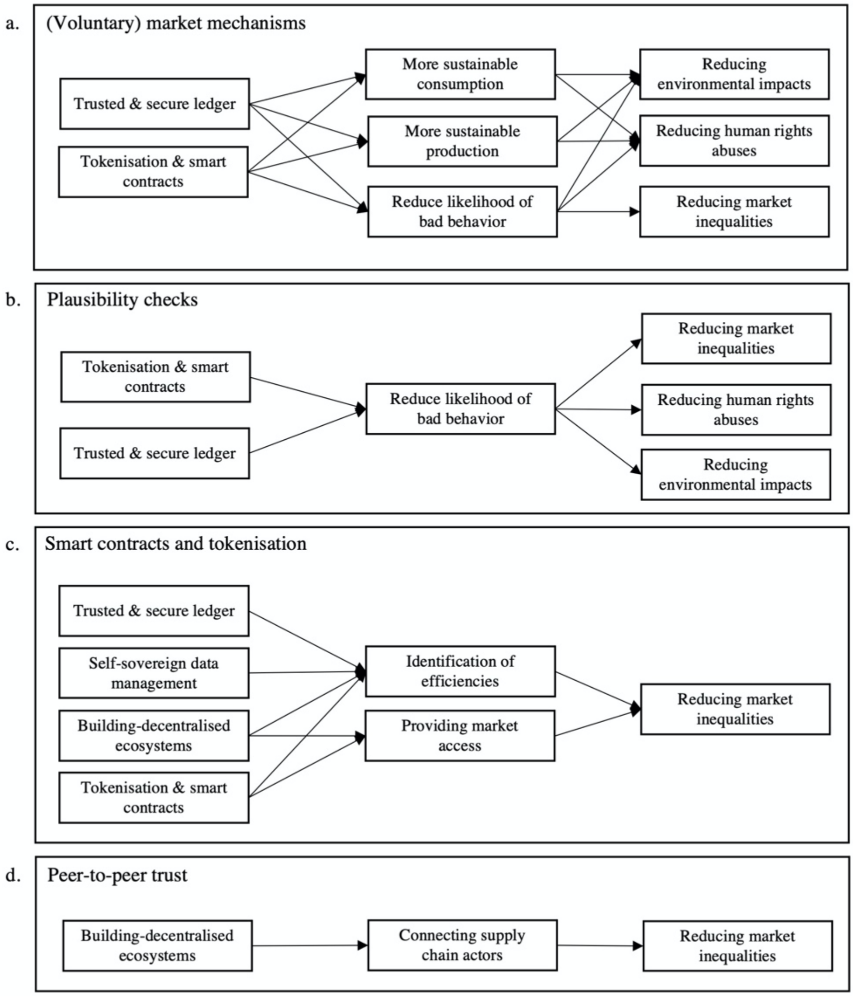

Figure 10: Four mechanisms of blockchain-based technologies creating positive social and environmental impacts in supply chains (reproduced from Köhler et al. 2021b)

6.3. HOW BLOCKCHAIN-BASED TECHNOLOGIES INTERACT WITH VOLUNTARY SUSTAINABILITY STANDARDS

The findings of Article V show that blockchain-based technologies can have a *co-existing, synergistic*, or *antagonistic* relationship with voluntary sustainability standards (Köhler et al. 2021a).

Most cases fall under the *co-existing* interaction (Köhler et al. 2021a). Blockchain-based technologies that co-exist with voluntary sustainability standards exist independently of them, i.e. the two do not interact. Co-existing blockchain-based technologies typically focus on increasing transparency through the use of blockchain technology. Some cases also use blockchain technology to provide access to financial services and use the data on the blockchain to conduct audits (Köhler et al. 2021a).

Several of the analyzed blockchain-based technology cases have a *synergistic* relationship with voluntary sustainability standards (Köhler et al. 2021a). These cases include existing standards and are certified by them. The voluntary sustainability standards provide an established framework with tested measures to increase positive impacts within supply chains as well as a trusted label and defined processes for auditing and participation. Blockchain-based technologies, meanwhile, increase transparency and data connectivity (Köhler et al. 2021a). Blockchain-based technologies can make data more accessible – depending on the system design – and facilitate information-sharing with different actors. This is particularly the case regarding labeling; blockchain-based technologies can be used to make existing labels interactive so that consumers can scan QR codes or NFC tags to access product-specific information (Köhler et al. 2021a). Combining blockchain-based technologies and voluntary sustainability standards thus leads to an improvement of the governance of supply chain sustainability.

Finally, one blockchain-based technology case was identified that presented an *antagonistic* relationship with existing voluntary sustainability standards (Köhler et al. 2021a). Within this antagonistic relationship, the blockchain-based technology case competes with the voluntary sustainability standard. The blockchain-based technology case implements its own measures to create positive social and environmental impacts, some of which use blockchain technology and some of which do not (Köhler et al. 2021a). Additionally, the blockchain data can be accessed and thus audited by anyone, creating accountability to the public (Köhler et al. 2021a).

The findings also indicate that blockchain companies have less complex and bureaucratic structures than many other companies (Köhler et al. 2021a). This may allow them to fast-test new ideas and iterate without having to navigate the slow processes of bureaucratic organizations. However, this also reduces accountability.

7. DISCUSSION: CAN BLOCKCHAIN TECHNOLOGY KEEP ITS PROMISE?

This section critically analyzes the results of the PhD project. Section 7.1 discusses the impact of blockchain technology itself, with a focus on renewable energies for mining (Section 7.1.1), an outlook on PoW blockchains based on recent developments (Section 7.1.2), and the limits of the LCA model as well as its use for making long-term predictions. Section 7.2 introduces the discussion on applications of blockchain-based technologies, focusing on their advantages and drawbacks (Section 7.2.1) and guiding principles for sustainability (Section 7.2.2). Finally, Section 7.3 discusses the findings of this PhD project in the context of prospective technology assessment.

7.1. THE IMPACT OF BLOCKCHAIN TECHNOLOGY ITSELF

The results from Articles I and III demonstrate the quantitative environmental impacts of Bitcoin. Over the years, both the energy consumption and carbon footprint of Bitcoin mining have increased from 31.3 TWh and 17.3 $MtCO_2$-eq in 2018 to 48.9 TWh and 32.87 $MtCO_2$-eq in 2019, then to 70.65 TWh and 58.79 $MtCO_2$-eq in 2020, and finally to 72 TWh and 60.07 $MtCO_2$-eq in the first six months of 2021. Coal-powered regions such as Xinjiang particularly contribute to the carbon footprint, while hydro-rich regions such as Sichuan add little. Throughout the life cycle of Bitcoin mining, the use phase is the major contributor, accounting for over 99% of the impacts. The main driving parameters are the hashrate, the energy efficiency of the mining equipment, and the mining locations. The consequential model has shown that the impact per TH mined is expected to decrease. However, evidence has shown that the hashrate grows at a faster speed. LCA has proven to be a tool that can provide a more holistic, solid, and scientific assessment of the environmental impacts of Bitcoin mining. However, it is also clear that the uncertainties about the future of Bitcoin mining are very high. Thus, LCA alone cannot serve as a tool for the prospective technology assessment of Bitcoin mining. Other methods of making useful predictions about the development of Bitcoin mining are needed to inform the use of LCA. Long-term predictions depend on parameters of unknown uncertainty, such as regulation, price developments, and competition with other blockchains in terms of user uptake. Different scenarios for the prospective technology assessment of Bitcoin could be developed with the help of experts from various fields. However, currently, reliable long-term predictions are lacking, as researchers are still struggling to understand the short-term developments.

It should further be highlighted that not every blockchain is the same. This PhD project focuses on the environmental impacts of Bitcoin mining. Bitcoin is a PoW blockchain. Additional PoW blockchains exist, such as Ethereum (as of July 2021), Monero, and Litecoin, but they do not all function exactly the same way. For example, Litecoin has a block generation time of 2.5 minutes, whereas Bitcoin has a block generation time of 10 minutes (Gervais et al. 2016). However, all of these blockchains apply a PoW consensus mechanism that requires energy for mining. Few studies have estimated the energy consumption and carbon footprints of other PoW blockchains beyond Bitcoin (Krause and Tolaymat 2018; Rauchs et al. 2018; Gallersdörfer et al. 2020). While Bitcoin is the largest cryptocurrency both in terms of market capitalization and energy consumption, other PoW blockchains are growing too. Estimations vary, but additional PoW blockchains may add somewhere between 25 and 50% to the energy consumption of Bitcoin mining (Rauchs et al. 2018; Gallersdörfer et al. 2020).

Other consensus mechanisms besides PoW exist as well. PoW is the first iteration of the mechanism used in blockchain technology, and more innovation will likely occur in this domain in the coming years. PoS has gained significant recognition as an alternative for PoW. Numerous blockchains such as Cardano and Celo already use this consensus mechanism (Cardano 2021; Celo 2021). Using an alternative to PoW can significantly reduce the environmental impacts associated with blockchains since mining is no longer needed. Ethereum, which currently still uses PoW, will transition to PoS – likely within this year. The Ethereum Foundation has estimated that the transition will reduce its energy consumption by 99.95% (Ethereum Foundation 2021).

The PhD project highlights that Bitcoin is not equal to blockchain and that using blockchain is not equal to using PoW. While Bitcoin is a blockchain, the terms cannot be interchangeably used. The criticism of

Bitcoin and other PoW blockchains' energy consumption is not against blockchain technology itself but rather against the use of PoW.

7.1.1. POW BLOCKCHAINS AND RENEWABLE ENERGIES

The modeling of Bitcoin mining is based on several assumptions due to the uncertainty of the given parameters. One of the main assumptions relates to the use of renewable energies for mining. This is also the subject of one of the main discussions regarding the impact of PoW blockchains. The Bitcoin community claims that 77.6% of mining in 2018 and 73% of mining in 2019 was powered by renewable energy sources (Bendiksen et al. 2018; Gibbons and Bendiksen 2019). However, these numbers have been contested. Cambridge University conducted the only known surveys among miners, and in 2018, their study found that about 28% of mining was powered using renewable energies (Rauchs et al. 2018); this number rose to 39% in their 2020 study (Blandin et al. 2020). Since this last survey, many things have changed, though. Information about the location of miners and the share of renewable energies in mining quickly becomes outdated.

While there are numerous anecdotes about the energy sources used in cryptocurrency mining, including mining with flared gas in Russia and the US (Carter 2021), and plans to use energy generated from volcanoes in El Salvador (Hernandez 2021), up-to-date data is missing. This lack of information is dangerous because such anecdotes can be used to support any position regarding mining, and they do not provide a clear picture of the entire system. In order to foster a clear discussion about renewable energies in mining, better and current data from the industry is needed (Reisch et al. 2021). Therefore, in this PhD project, a sensitivity analysis of the electricity mix was conducted, showing the range of possible results for the related carbon footprint as well as several scenarios based on different geographical distributions of miners. While this analysis provides insights on the impacts of mining in different mining locations, the model is not able to illustrate the short-term fluctuations in mining locations and electricity sources used.

Using renewable energies for Bitcoin mining can also lead to burden shifting. In Plattsburg, New York, miners flocked to the city due to the cheap electricity from hydropower. This increased the energy demand to the point where the city was no longer able to provide cheap electricity, affecting both local citizens and businesses (D'Ambrosio

2018) and forcing it to import electricity from elsewhere. The city of Plattsburgh was the first to pass a moratorium to stop new miners from settling in their town (D'Ambrosio 2018). This example shows that simply moving activities to locations where the energy mix is composed of a high percentage of renewable energies does not necessarily reduce the impact of mining and might result in burden shifting. The mining industry would have to install their own – additional – renewable energy capacities to ensure that the carbon footprint for mining is truly reduced. However, there is no evidence that this is taking place. Ideas have been proposed to introduce mining facilities entirely powered by solar power (Square 2021), but so far little has been observed in this regard. Instead, fossil fuel power plants such as Greenidge Generation Station in Dresden, New York, have reportedly reopened solely for Bitcoin mining (Hilburg 2021). The LCA model in the PhD project was unable to include the burden shifting due to displaced energy demand of existing consumers.

Other indications exist that fossil fuel is the main energy source powering Bitcoin mining. China has taken concrete steps to shut down mining industries for that reason. In March 2021, Chinese officials targeted miners in Inner Mongolia, China. The Cambridge study estimated that the miners in Inner Mongolia made up 8% of the network's hashrate in 2020 (Cambridge Centre for Alternative Finance 2020). When the region fell short of its emission reduction targets for 2019, the province announced new legislation banning mining in Inner Mongolia (Aljazeera 2021). In Xinjiang, another main location for mining (36% of the hashrate in 2020; Cambridge Centre for Alternative Finance 2020), a power outage at a coal power plant led to an overall hashrate drop between one third and almost 50% (de Vries et al. 2021; Redman 2021). Hashrates of popular mining pools dropped between 18 and 33% (Redman 2021). While these numbers may not correspond exactly to the miners located in Xinjiang, they provide insight into how many miners might have been located there and on how much mining is currently depending on coal.

In the past years, the largest and most steady source of renewable energies for mining has come from hydropower in Sichuan and Yunnan provinces in China (Blandin et al. 2020). An estimated 25% of the hashrate originated from both provinces in 2019 and 2020 (Cambridge Centre for Alternative Finance 2020). Recent changes (June 2021) in

Chinese policies have shut down all mining activities in China, including those in Sichuan and Yunnan provinces (Sigalos 2021). These changes affect not only the largest source of renewable energies used in cryptocurrency mining but also 65-75% of all miners – all of whom were located in China until recently. These miners are expected to move to other world regions, with Texas and Kazakhstan being mentioned as likely destinations (Sigalos 2021). Both locations have high shares of natural gas in their electricity mix along with some hydropower (Kazakhstan) and wind energy (Texas; Wernet et al. 2016). The LCA modeled in this PhD project was also unable to include uncertainty due to changes in legislation and policy, and drastic changes were only modeled retrospectively in the attributional model.

Overall, it should be highlighted that increasing the share of renewable energies in mining is only one lever that can reduce the carbon footprint of PoW blockchains. Reducing the overall amount of energy needed for mining is another one. Chinese provinces such as Inner Mongolia have already taken action because their local demand for mining was so high that they were no longer able to meet their agreed-upon Paris Agreement targets. Increasing the overall energy demand as Bitcoin has done over the past years, would require also increasing the installation of renewable energies by at least as much to have no net negative carbon footprint. Considering, the amount of renewable capacity that is globally added per year, it is questionable if simply “making mining green” is sufficient. In both 2018 and 2019, about 180 GW of renewable energy capacity was added globally. In 2020, this number increased to about 260 GW (IRENA 2021). Assuming that the full capacity was used – which is unrealistic, particularly for volatile energy sources like wind and solar power – the newly-added renewable energies could have produced an additional 1,578 TWh in 2018 and 2019 each and 2,278 TWh in 2020. This is less than the increase in energy consumption in these years (Ritchie and Roser 2021). Considering that Bitcoin mining required 31.29 TWh in 2018, 48.90 TWh in 2019, and 70.65 TWh in 2020, 2-3% of the renewable capacity currently added would need to be used for Bitcoin mining each year.

7.1.2. THE FUTURE OF BITCOIN AND OTHER POW BLOCKCHAINS

While the environmental impact of Bitcoin mining cannot be fairly compared to anything else, it can be useful to put the values into perspective to emphasize the scale of its energy consumption and impacts. All data centers in the world consume about 200 TWh per year (de Vries 2021). A recent grey literature study estimates the energy consumption of the global financial system, including data centers, bank branches, and ATMs, to consume about 240 TWh per year (Rybarczyk et al. 2021). Bitcoin alone was estimated to consume 70.65 TWh per year in 2020 and 72 TWh in the first six months of 2021. While this is still below 0.1% of the global energy consumption (Ritchie and Roser 2021), it demonstrates that PoW blockchains are responsible for a considerable amount of energy consumption, particularly considering that the technology is not (yet) as widely used as the existing financial system.

The example of Inner Mongolia, which shut down Bitcoin mining due to its inability to meet emissions reduction targets, further shows that Bitcoin mining already clashes with local climate targets. The industry has reached a scale where in the context of local and global efforts to reach greenhouse gas emission (GHG) reduction targets, it becomes a hindrance (Jiang et al. 2021). Truby (2018) even suggests that blockchain technologies pose a serious threat to reaching the GHG reductions agreed upon in the Paris Agreement, and Jiang et al. (2021) state that without any intervention, the carbon emissions of Bitcoin mining will be a non-negligible barrier against sustainability efforts in China. Truby (2018) argues that interventions are necessary and examines different government intervention choices, such as limiting the import and production of energy inefficient mining equipment and imposing profit surcharges on corporation or personal income taxes. In a broader context, it is also argued that negative externalities such as pollution or GHG emissions should be internalized. This means that the costs of such externalities should be included in the price of the product or service that causes them to exist. Therefore, cryptocurrency mining – just like other industries – should be subject to measures that internalize externalities. The following paragraphs present several approaches that could be used to address the significant environmental footprint of (PoW) blockchains from the perspective of different actors, including industry actors, regulation bodies, and society.

The industry initiative *Crypto Climate Accord* agrees that action needs to be taken. Multiple members within the crypto community have signed the Crypto Climate Accord, making a public commitment to reduce emissions from the energy consumption of all their crypto-related activities by 2030 (Crypto Climate Accord 2021). The signatories should report their progress toward the net-zero emissions targets. Overall, the goal is to power blockchains entirely by renewables, which can be achieved by either refraining from the use of energy-inefficient consensus mechanisms like PoW (and renewable energies) or powering PoW blockchains with 100% renewables (Crypto Climate Accord 2021).

While some blockchains are willing to transition to a different consensus mechanism, such as Ethereum (Ethereum Foundation 2021), it is unrealistic to believe that all blockchains will follow their example. The Bitcoin community has been particularly known for wanting to continue using PoW (Held 2018; Banks 2021). Thus, tremendous action towards building renewable energy capacities would be required to achieve the goal of powering the Bitcoin blockchain using 100% renewable energy. It is questionable if this is realistic, particularly considering that no large-scale plan has been presented yet. Stranded energy is a limited source and does not guarantee long-term use. For example, the stranded energy from hydropower in Sichuan was always used as a positive example, but the recent legislation change in China shows that these energy sources may not always be available. Additionally, using renewable energies from the local grid may lead to the burden shifting due to displaced energy demand of existing consumers towards other sources of energy supply, as the example of Plattsburgh has shown.

Other ideas for increasing the use of renewable energy sources for Bitcoin mining have been proposed, such as that of the *Bitcoin Clean Energy Initiative* (Square 2021). This initiative proposes combining Bitcoin mining with renewable energy production and storage projects and presents this combination as an opportunity to accelerate the global energy transition (Square 2021). This proposal is claimed to increase the profitability of solar and wind projects, as Bitcoin mining can be a flexible and interruptible load, therefore consuming temporary excess energy (Square 2021). However, critics have questioned these proposals and called them wishful thinking (Kelly 2021). Many of these proposals indeed raise more questions than they solve (Kelly 2021). For example, it is not clear how such a proposal would be profitable for the miners or if they continue using grid energy for mining when no excess energy is available. While building own renewable energy capacities for mining is a reasonable approach to reducing the carbon footprint of mining, the proposals lack a holistic and life cycle perspective and are often based on the assumption that energy consumption can continuously increase as long as renewable energy is powering said consumption. However, research has shown that increased energy production is outpacing decarbonization, meaning carbon emissions are still increasing overall (Jackson et al. 2018). This finding is particularly interesting since the energy consumption of cryptocurrency mining has continued to increase over the past few years, while no significant low-carbon capacities have been built. Considering the need to reduce overall emissions to remain well below 2°C of warming to reduce the likelihood of the severe negative effects of climate change, solely addressing the source of energy consumption is insufficient.

Government intervention can be another approach to reduce the environmental impacts of blockchains. The question is how local, regional, and international authorities can regulate PoW blockchains that interfere with their climate goals and impede the objective of remaining well below 2°C as outlined in the Paris Agreement. Regulators have already taken action in numerous locations. Additionally, research has explored different regulation approaches (Truby 2018; Jiang et al. 2021). Truby (2018) discusses different regulation options, while Jiang et al. (2021) compare three regulation scenarios against a business-as-usual baseline for China.

Specific legislation has been used to regulate local mining sites in different regions. The city of Plattsburgh in New York has limited the number of miners with a moratorium, and China banned mining first in Inner Mongolia, then throughout the country. With the migration of miners from China to other jurisdictions, it is uncertain if and what measures may be taken elsewhere. Jiang et al. (2021) also propose strict regulation on mining companies in areas with carbon-intensive energy supplies. The study suggests that regulators can convince miners to relocate to regions with more energy production from renewable energies. While this suggestion offers positive results regarding reducing the carbon footprint of mining, it does not seem to take burden shifting due to displaced energy demand of existing consumers into account.

Both Truby (2018) and Jiang et al. (2021) further propose the regulation of mining equipment. Minimum requirements regarding the energy efficiency of mining equipment could be introduced. However, Jiang et al. (2021) find that this scenario performs the worst compared to other regulation options, and there is good reason to be skeptical about this approach. Regulating the efficiency of mining equipment will likely not reduce the energy consumed for mining; rather, it will likely increase the overall hashrate, as more efficient equipment can compute more THs per second using the same energy consumption. This would further lead to the abandonment of existing less-efficient equipment. The real bottleneck in this approach would arise from the availability of efficient equipment, as microchip shortages limit the production of mining equipment (de Vries et al. 2021).

Instead of targeting the miners, other proposed ideas address the issue at the point of cryptocurrency use. Legislators could tax each transaction (Truby 2018). This could either be done through cryptocurrency exchanges, which would be a relatively straightforward process, or automatically through smart contracts on the blockchain, which would require the support of blockchain communities. One advantage of such an approach would be that it would not matter where the miners were or to which location they moved. Instead, it would depend on the locations of users, who are less mobile. A tax on consumption may lead users to switch to cheaper blockchains – those that do not use as much energy – or incentivize renewable energy use for mining.

de Vries et al. (2021) further suggest that the carbon footprint of Bitcoin should be allocated proportionally among the investors. Unlike the taxation suggestion, this would be based not on individual transactions but on total investments. For example, Tesla held about 1.43% of all bitcoins in circulation and still accessible in June 2021 (de Vries 2021). This means that Tesla is responsible for 0.24 Mt CO_2 (1.43% of 90.2 Mt CO_2 estimated for 2021; de Vries et al. 2021). This approach could be tied to the Scope 3 emissions under the GHG Protocol, for which companies must take responsibility. However, the approach does not capture individual investors. The last two approaches highlight the importance of accurate estimations of carbon footprints, as they would be the basis for these measurements.

Government intervention can also play a different role. El Salvador is the first country to have taken steps to adopt Bitcoin as a legal tender, which takes effect in September 2021 (Arnold and Strohecker 2021). This decision has spurred significant criticism, particularly regarding Article 7 in the Bitcoin Law that has been passed. This article states that every agent must accept Bitcoin as a payment, which some even called “forced tender” (Hanke and Hinds 2021). With other Latin American countries rumored to follow suit, it is likely that Bitcoin may soon be useful for purchasing and selling everyday goods on a large scale.

The technology development process can also be shaped by influential persons as well as society. Users of blockchain-based technologies should learn about these technologies and the impact they may have. The users and the public play a role in shaping the technology, and if they accept or reject the externalities of PoW blockchains, they could affect the technologies’ developments. Powerful individuals can also steer the discussion and perception of technology. Elon Musk’s tweet in May 2021 about his and Tesla’s concerns regarding the fossil fuel dependency of Bitcoin (Musk 2021) again increased the interest in and coverage of this topic. It may have also caused a significant drop in price (Blockchain.com 2021b).

Several approaches can be taken to address the significant environmental footprint of PoW blockchains. Industry actors, regulation bodies, and society can all influence the development process of (PoW) blockchain. While it can be difficult to regulate and shape a decentralized technology such as blockchain, different levers exist through which to do so. The question is which ones will be pulled.

7.1.3. LONG-TERM PROJECTIONS AND MODEL LIMITATIONS

The previous sections have shown that uncertainties regarding Bitcoin and cryptocurrencies are high, including price volatility, miner volatility, policy intervention, and public responses to media coverages, to name a few major uncertainties. The LCA model in this PhD project was not able to address these uncertainties. This means that a short-term understanding of the Bitcoin system must be further developed, particularly before making long-term projections. Given these uncertainties, only a few studies have so far attempted to make long-term predictions (Mora et al. 2018; Jiang et al. 2021).

Mora et al. (2018) projected that Bitcoin alone could be responsible for surpassing 2°C in global warming within a few years. The study has, however, been heavily rebutted (Dittmar and Praktiknjo 2019; Houy 2019; Masanet et al. 2019). The study exhibited structural limitations, used outdated values, and portrayed a departure from historic trends.

Jiang et al. (2021) projected the effects of four different policy scenarios of Bitcoin mining on energy consumption and the carbon footprint. While the study does highlight several limitations including price volatility, which the study considered *"inappropriate for long-term assessment",* it nonetheless assumes that the long-term price will be predominantly influenced by the Bitcoin halving, thereby neglecting the effects of short-term volatility. This is a significant simplification. The study also assumes that all miners of Chinese mining pools are located in China, likely overestimating the share of miners in China (cf. Cambridge Centre for Alternative Finance 2020). Furthermore, it is assumed that 40% of miners use coal as an energy source while the rest use hydropower, which is a more optimistic assumption than other studies make (Cambridge Centre for Alternative Finance 2020). Additionally, the study does not consider burden shifting due to displaced energy demand of existing consumers or the temporal unavailability of hydropower during the dry season in the site regulation scenario. There are indications that miners moved from hydro-rich regions like Sichuan to coal-rich regions like Xinjiang during dry seasons and vice versa during wet seasons (de Vries 2019). Finally, the study only investigates the effects on China, making the assumption that miners move to other countries once mining in China becomes too expensive. Therefore, the results on reducing the overall carbon emissions of Bitcoin mining are limited.

These examples show that making long-term predictions entails significant uncertainties that need to be properly addressed to provide meaningful results. The value of projections is limited when they do not consider more comprehensive scenarios or include uncertainty and sensitivity analysis. Thus, the present PhD project only provides short-term projections on a per TH basis. This approach is valuable because it provides insights into the nonlinearity of scaling up Bitcoin mining. It also underscores the sensitivity of the model to equipment efficiency and mining location. However, the model was unable to make long-term predictions exactly due to the uncertainties and fluctuations the other studies exhibit. The model does not include legislature changes, burden shifting due to displaced energy demand of existing consumers, or viral tweets that may influence buying or selling patterns. LCA alone is not sufficient to tackle these uncertainties. These issues could be addressed by developing extensive scenarios with experts from different domains, including economists, computer scientists, and legal experts.

7.2. THE IMPACT OF APPLYING BLOCKCHAIN-BASED TECHNOLOGIES

The findings of the PhD project show that blockchain technology is not a stand-alone technology but rather part of a system of technologies. Therefore, it may not be possible to distinguish between the impacts of blockchain technology and the impacts of the entire system. Blockchain-based technologies vary considerably in their design (Köhler and Pizzol 2020; Köhler et al. 2021a). The project also indicated that depending on their design, blockchain-based technologies can have different relationships with existing alternatives. The project has found that blockchain-based technologies in supply chains can co-exist with voluntary sustainability standards, compete with them, or generate synergies (Köhler et al. 2021a). Consequently, the goal of an implementation and the associated system design for reaching this goal are crucial. This idea relates to prospective technology assessment and the intention and potential orientation, which can reveal significant information about the technology early in its implementation (Liebert and Schmidt 2010). Although blockchain-based technologies vary in their system design, the PhD project generated a middle-range theory of how blockchain-based technologies operating in supply chains can create positive social and environmental impacts within them and illustrated four specific impact pathways. These results show several ways blockchain-based technologies can be employed to generate a positive impact. The middle-range theory should be further tested to see if the findings remain true for long-term implementations. The middle-range theory additionally serves as a starting point for understanding the different ways in which blockchain technology can be applied in supply chains and beyond.

7.2.1. ADVANTAGES AND DRAWBACKS OF BLOCKCHAIN-BASED TECHNOLOGIES

While blockchain-based technologies are implemented in a system of technologies, certain direct advantages and drawbacks of including blockchain technology can be observed. Some of the major effects are critically discussed in the following paragraphs.

Trust has been highlighted as one of the main advantages of blockchain technology (Mahyuni et al. 2020). This trust is believed to stem from the fact that data on the blockchain cannot be retrospectively changed and “double-spending” is not possible. These restrictions can guarantee a certain plausibility (Köhler et al. 2021b). If certificates for 2 kg of organic coffee have been registered by a certification body, it is not possible to later sell 4 kg of certified coffee, as only certificates for 2 kg exist. Blockchain technology prevents the manipulation of data, which can increase trust. However, blockchain technology does not guarantee that the data put on the blockchain is correct. If a fraudulent actor creates certificates for 4 kg, but only 2 kg of certified coffee exists, the additional certificates can be used to wrongfully sell uncertified coffee as certified. Only when high-quality and useful data are entered onto the blockchain are the benefits of having a secure and immutable ledger valuable. Several methods are being used to address this problem, ranging from incorporating technology (e.g. IoT or AI) to employing a third party to verify persons who can register new assets (Köhler and Pizzol 2020). Nevertheless, using blockchain technology can reduce the possibilities of fraudulent behavior as well as honest mistakes.

Another significant advantage is *transparency* (Mahyuni et al. 2020). If blockchain-based technologies are designed so that the data can be accessed and verified by outside parties, transparency is created and accountability to the public can increase. If anyone can check information, this can further increase trust in the data. However, crucially, this transparency depends on the system design of blockchain-based technologies. Important system design questions include what kind of data are on the blockchain (e.g. relevant) and how accessible the data is (e.g. publicly accessible or not). Furthermore, projects are still in the early stages. Some projects that intend to have data publicly available for consumers are still developing this solution (Köhler et al. 2021a). Therefore, transparency is not inherent to blockchain technology, but prioritizing it in the system design can make it an important part of blockchain-based technologies.

The use of blockchain technology for *traceability* in supply chains has also been described as a major advantage (Mahyuni et al. 2020). The ownership rights of a product can be transferred using blockchain technology. This can then create a chain of custody, which is lacking in many supply chains (Köhler et al. 2021b). For purely digital products – e.g. cryptocurrency tokens – using blockchain is straightforward, but with physical products, it is more complicated. As a first step, the supply chain needs to be digitized. Implementing blockchain-based technologies along the entirety of the supply chain means producers must have digitized processes. Otherwise, blockchain-based traceability stops at the point in the supply chain where digitization has not been established. However, digitizing paper-based processes requires time. Additionally, it cannot be guaranteed that the changes to the physical product (e.g. processing, ownership change, etc.) are replicated on the digital ledger. The employment of other technologies is considered to overcome this problem (Köhler and Pizzol 2020). Overall, these processes show that where humans are involved (e.g. for registering new assets or product changes), higher manipulation risks exist.

Financial services facilitated by blockchain-based technologies are one of the immediate applications of blockchain technology. While financial services can constitute a separate application, they can also be part of blockchain-based technologies in specific fields, e.g. supply chain management. This PhD project has illustrated the inclusion of financial services within supply chain applications. Cryptocurrencies and tokens are an integral part of blockchain technology and can provide benefits to users as a secure way to conduct transactions. However, a downside of some of these services may be the conversion of fiat currency to cryptocurrency to send abroad, followed by the conversion to the local fiat currency. Using such blockchain-based technologies also requires users to be proficient in their use, which for certain groups may require additional training and campaigns; otherwise, these technologies will benefit those who are already technology savvy and increase existing power asymmetries.

Tokenization in combination with *smart contracts* presents another advantage that blockchain technologies can offer. Articles II, IV, and V all highlight this point (Köhler and Pizzol 2020; Köhler et al. 2021b, a). Tokenization can be used for all kinds of applications and incentivization. However, testing of this potentially powerful feature is in early stages. It could be used to automatically tokenize behavior. For example, farmers could collect tokens for specific sustainable behavior (e.g. CO_2 emissions reductions) that may then allow them to receive favorable terms from their buyers. This is just one example, and multiple new ways of incentivizing sustainability using tokenization can be imagined. However, this advantage also brings ethical risks that should be considered. Do we want to tokenize all aspects of life? What are the consequences of tokenizing, e.g. all carbon-emitting activities and behaviors? How can we prevent such incentives from being biased toward actors who are already more sustainable? In the context of prospective technology assessment, tokenization applications should continuously be assessed regarding their success and potential unintended consequences.

In the interviews for Article IV, it was also mentioned that blockchain technology can be a way to *get parties on board* (Köhler et al. 2021b). Particularly larger companies have stated that they would not be willing to join a centralized system, especially if competitors are involved, but they would join a decentralized consortium for their industry (Köhler et al. 2021b). It was also stated that the larger the network becomes, the more appealing blockchain-based technologies are for the actors (Köhler et al. 2021b). Decentralized technologies such as blockchain-based technologies are in a unique position to include many actors – including competing ones – and can thereby drive technology adoption. Additionally, the use of blockchain technology offers a chance to build inclusive networks (UN 2019). However, all actors must participate for such a system to work. If all these actors are also involved in defining the system design, they have a unique opportunity to co-create a system that benefits all. This, however, is also one of the biggest challenges. It takes time to come to an agreement on system design, including the governance mechanisms and which blockchain is used. Furthermore, it is not clear if blockchain technology will foster the building of inclusive and democratic structures as promised or further strengthen existing power structures (Lange and Santarius 2020). Large companies are currently exploring the use of blockchain technology, thereby participating in shaping its development (Lange and Santarius 2020).

Another advantage of using blockchain technology is secure and self-sovereign *data management*. The study participants in Article IV highlighted that by using blockchain technology, actors within the supply chain can maintain ownership of their data and decide themselves with whom they will share their data and for what period. Cryptographic algorithms can also be used to prove something, e.g. the minimum requirements of capital, without revealing their actual capital. This benefit was highlighted as a significant improvement compared to existing technologies. However, it should be noted that while an actor has control over who they want to share data with, market pressures may dictate who they have to share data with to conduct business.

Using blockchain-based technologies can also be a way to *get projects funded*. It can increase the willingness of companies to pay for traceability and sustainability solutions, as the funding would come from the innovation budget instead of the back-office or sustainability budget (Köhler et al. 2021b). This is an interesting point. The study participants for Article IV highlighted the fact that, as blockchain-based technologies in supply chains are innovation projects rather than pure sustainability projects, companies seem more willing to invest.

Blockchain technology is also still an emerging technology. We don't know what we don't know yet. The technology must overcome remaining technological hurdles (e.g. scaling), the legislature is not yet ready to navigate decentralized technologies (e.g. China's recent ban on mining), and implementations must undergo rigorous testing phases. It is as yet unclear how an implementation will respond to malicious behavior. For example, a study participant for Article IV pointed out that if an actor is caught making errors – either with honest intentions or in an attempt to commit fraud – it is still unclear what the consequences will be. Consequences to malicious behavior may be developed before implementation of blockchain-based technologies but can only be assessed after they were triggered.

The listed points are some of the main direct advantages and drawbacks observed within this PhD project that come from using blockchain-based technologies. Long-term advantages and drawbacks will need to be determined as time passes. Furthermore, the system design determines the real impacts of blockchain-based technologies. Blockchain technology does not singlehandedly reduce social and environmental impacts. This technology is a tool that can be used to trace materials, manage certificates, bring transparency data, and thus create accountability – if it is designed that way. However, reducing social and environmental impacts still requires specific measures, policies, and behavioral changes. Blockchain technology can be one tool (as part of a system of technologies) used to implement measures and policies and incentivize behavioral change.

7.2.2. PRINCIPLES FOR SUSTAINABLE APPLICATIONS

The importance of system design has been highlighted sufficiently in previous sections. Thus, the question arises of which principles should be considered for system designs. Lange and Santarius (2020) propose three guiding principles for digitalization that they consider to be fundamental in achieving sustainable and equitable solutions: digital sufficiency, strict data protection, and focus on the common good. While these guiding principles have been proposed for digitalization, they may also be relevant to the shaping of development processes for technologies. In the following paragraphs, these guiding principles are discussed in the context of blockchain-based technologies.

Digital sufficiency refers to using technologies as much as necessary yet as little as possible to manage energy and resource requirements (Lange and Santarius 2020). Blockchain technology has been proposed as a solution for everything (Frederik 2020) and is sometimes even said to be a solution in search of a problem (Bull 2018). Applying the technology only to cases where it brings benefits should therefore be a priority. It should also be considered that other technologies may be a better fit to solve a given problem. Technical sufficiency can be achieved by using devices with a long lifetime and as few devices as necessary (Lange and Santarius 2020). This PhD project has illustrated that cryptocurrency mining is resource-intensive. Not only are the energy requirements high but mining equipment is also only used for short periods (de Vries 2019). Therefore, blockchains that use PoW or other resource-intensive consensus mechanisms do not align with the principle of digital sufficiency. Additionally, all blockchains are maintained by many peers simultaneously. For example, Ethereum had about 5,300 live mainnet nodes online in July 2021 (ethernodes.org

2021). While these structures may seem redundant, they are the backbone of what makes blockchain technology function without a central authority. Another factor is the volume of data that is stored on-chain and off-chain and collected in general through blockchain technology. A balance between functionality and sufficient data should be found. Finally, digital sufficiency also refers to preventing rebound effects caused by newly realized efficiencies (Lange and Santarius 2020). Behavioral changes and structures to support this prevention are, therefore, key to any technology implementation.

The principle of *strict data protection* should guide the use of technology to limit monitoring, surveillance, and discrimination (Lange and Santarius 2020). Blockchain technology can be used to achieve this principle. Having a way to securely share data and regain control of individual data (Köhler et al. 2021b) can be a step towards reducing the power asymmetries in the existing system. However, it should still be questioned what data and how much data are collected. The use of personal data should be limited, particularly when they are stored on the blockchain. Strict rules on collection, storage, use, and sharing can support strict data protection (Lange and Santarius 2020).

Finally, *focus on the common good* refers to building open source and cooperative platforms (Lange and Santarius 2020). Decentralized structures based on blockchain technology can be an opportunity to build inclusive and collaborative technologies. While current structures are largely based on five big technology companies, i.e. Facebook, Amazon, Apple, Google, and Microsoft, blockchain technology offers an opportunity to reverse this trend. For example, the Web3 Foundation is supporting the development of a decentralized and fair internet with users in control of their own data and identity (Web3 Foundation 2021). However, this is not a guaranteed development. Large companies are already invested in blockchain technology (Lange and Santarius 2020). This calls into question whether blockchain technology will ultimately be used for the common good or for company profits. One advantage of blockchain-based technologies is that they can be designed for public transparency (e.g. holding companies and governments accountable). Building digital infrastructure for the common good also requires involving all kinds of people in the development of a technology. This includes, for example, programmers who represent the general public to ensure that the technology reflects their needs as well as the needs of the technology's users.

Alignment with these principles does not come naturally, but it must be demanded, promoted, and implemented systematically by policymakers, companies, societies, and users (Lange and Santarius 2020). The three guiding principles provide some general guidelines that are also relevant for blockchain technology. 1) Blockchain-based technologies should be applied only to cases where they bring actual improvements compared to the alternatives. Additionally, blockchain technology itself should be designed in a way that is not resource or material-intensive. 2) While blockchain technology may provide a secure way to share data, rules regarding monitoring, surveillance, and discrimination should exist. 3) Using blockchain technology is a chance to build inclusive and fair solutions, but this will not come naturally. These solutions need to be demanded and actions need to be taken by, for example, governments and large actors who can adopt these or similar principles.

7.3. BLOCKCHAIN-BASED TECHNOLOGIES IN PROSPECTIVE TECHNOLOGY ASSESSMENT

In Section 2, the three requirements of prospective technology assessment by Liebert and Schmidt (2010) were introduced, namely early-stage orientation, intention and potential orientation, and shaping orientation.

It is worth questioning whether *early-stage orientation* is still possible for PoW blockchains. It has been known for years that PoW blockchains are energy-intensive by design, but little action has been taken in response. Although Ethereum is transitioning to PoS, other blockchains have no such plans. As Truby (2018) argues, failure to intervene in Bitcoin mining may increase the chances of path dependency. The same is true for other PoW blockchains. However, the situation is somewhat different for blockchain-based technologies. Many projects are built on blockchains that do not use PoW or Ethereum, which is transitioning to PoS. Additionally, blockchain-based technologies vary significantly in system design. Thus, prospective technology assessment should also be conducted at the project level and should be considered a continuous process for reassessing the impacts of a project at various stages. Therefore, it is particularly concerning that many projects do not measure their impacts (Köhler et al. 2021b).

The findings in Article V make the *intention and potential orientation* especially interesting to address. Blockchain-based technologies in supply chains can have different relationships with existing sustainability governing mechanisms. The intentions behind these technologies can help determine how their relationship to existing solutions can be described. A blockchain-based technology solution can intentionally compete with an existing solution, collaborate with it, or target a separate market altogether (Köhler et al. 2021a). Several cases in Article V decided to incorporate existing voluntary sustainability standards, while one case chose to compete with existing solutions. Similarly, blockchain-based technologies can be intended to foster sustainability. Technology is a tool that can be used to accomplish different purposes. Thus, blockchain technology can be used – depending on the system design – to achieve different goals. While blockchain projects may not always communicate their full intentions, examining a project's intention can support the identification of negative side effects and risks early on. For example, examining the PoW consensus mechanism indicates that it is intended to be resource-inefficient. Strong incentives exist for miners to consume energy and to increase their share in mining. PoW consumes an extensive amount of energy by design (de Vries 2018). Thus, intention and potential orientation can be used to identify potential social and environmental impacts. However, it also illustrates that actions need to be taken to counteract such potential negative impacts.

The previous sections have shown that the *shaping* of technology development can be influenced by various actors, including technology developers, companies, users, governments, research, and society. Technology developers and companies implementing the technology play a particularly active role in choosing the design and implementation options. Users, in contrast, react to technology implementations (or not) and by sending these signals, they can affect what is developed further and what is not. The previous sections have also shown that governments can take an active role in shaping a technology. They can accomplish this by directly regulating the technology or by providing guiding principles and frameworks for implementing democratic and inclusive solutions. The role of research in shaping technology development can be important as well. Findings can inform different actors, such as technology developers or policymakers, and thereby indirectly contribute to shaping technology development. For example, this PhD project has informed media articles about the impact of blockchain technologies and public discussions about blockchain and sustainability (cf. dissemination). The findings of the PhD project will be further shared with the study participants in Article IV (after publication) and potentially shape their implementations. Finally, society can play a role in shaping technology development. Dissatisfaction with a technology's impact can apply pressure to technology developers and policymakers. For example, the opposition led by the NGOs Earthjustice and the Sierra Club against the repowering of Greenidge Power Station to mine Bitcoin put pressure on local authorities (Sierra Club 2021).

8. THE FUTURE OF SUSTAINABLE BLOCKCHAIN TECHNOLOGIES

This section will first answer the research questions of this PhD project and then highlight the contributions and impact of the PhD project (Section 8.1). Finally, recommendations for future research are proposed (Section 8.2).

Using the cases of Bitcoin mining and blockchain-based technologies in supply chains, this PhD project explored the environmental and social impacts of blockchain technology. The Main Research Question and Hypothesis were addressed by two sub-questions and sub-hypotheses.

First, **Research Question 1** was examined:

> *What is the environmental impact of (PoW) blockchain technology from a life cycle perspective based on the example of Bitcoin?*

This research question was answered by validating the following hypothesis:

> *LCA can provide a holistic, solid, and scientific assessment of the environmental impacts of Bitcoin mining.*

The hypothesis was validated by Article I, Article III, and the additional assessment in this PhD thesis. The following points were highlighted: 1) Section 5 of this thesis provides an overview of the environmental impacts of Bitcoin mining from 2018 until mid-2021. 2) This PhD project provides reproducible and comparable results that are based on an established methodology and databases. Environmental impacts beyond the carbon footprint could also be assessed using this approach. 3) LCA allowed this assessment to adopt a life cycle perspective, investigating the environmental impacts during different phases. This assessment revealed that the main contribution to the environmental impacts of Bitcoin mining occurs during the use phase. 4) Sensitivity and uncertainty analyses showed that the results are particularly responsive to changes in location, the energy efficiency of the mining equipment, and the hashrate. Using multiple scenarios involving different miner locations provided insights into the uncertainty and range of possible results. 6) This study represents a significant improvement compared to studies that only consider the use phase and calculate the annual energy consumption based on the results of a single day (e.g. de Vries 2021 estimated the energy consumption and carbon footprint for 2021 based on one day in January). 7) The PhD project has further shown the nonlinearity of scaling Bitcoin mining as an emerging technology. 8) The LCA model was unable to address the high volatility and uncertainty of Bitcoin mining – particularly in a long-term prospective assessment.

Next, **Research Question 2** was reviewed:

> *How can blockchain-based technologies foster sustainability based on the example of applications in supply chains?*

The research question was answered by validating the following hypothesis:

> *By taking a systemic perspective, it can be assessed if and to what degree blockchain-based technologies bring positive social and environmental impacts.*

The hypothesis was validated by Articles II, IV, and V. The following points were highlighted: 1) Blockchain-based technologies should be considered as part of a system of technologies of which blockchain technology is one component. This requires a systemic perspective. 2) The PhD project was informed by real experiences of blockchain-based technologies in supply chains. 3) A middle-range theory and four impact pathways were identified showing *how* blockchain-based technologies can initiate positive social and environmental impacts in supply chains. However, it is too early to observe long-term impacts, as the implementations are still in the early stages. 4) The impacts of many blockchain-based technology projects are not measured. This is particularly concerning from a prospective technology assessment perspective, as it is easier to implement changes in the early stages. The lack of measured impacts means that there is no basis for assessing if a project is successful, needs to be adapted, or should be discontinued. 5) The PhD project investigated how blockchain-based technologies interact with sustainability solutions that already exist. Blockchain-based technologies can co-exist, compete, and collaborate with these solutions. The intention and design of technology systems are important factors determining how blockchain-based technologies relate to existing solutions.

Finally, the **Main Research Question** was analyzed:

> *What are the environmental and social impacts of blockchain technology beyond the hype and with a solid scientific basis?*

The Main Research Question was answered by validating the following hypothesis. Research Questions 1 and 2 were used as the basis to address the Main Research Question.

> *While the first iteration of this new technology – namely Bitcoin and the proof-of-work algorithm – are detrimental for the planet, blockchain technology can be used as a tool to foster sustainability.*

The hypothesis was validated by Research Questions 1 and 2. The PhD project showed the following: 1) PoW blockchains have a high carbon footprint. Shifting to a non-PoW blockchain can significantly reduce environmental impacts. 2) Blockchain technology can be a tool to address sustainability as part of a system of technologies. However, it is crucial that the system is deliberately designed to have a positive impact. 3) PoW blockchains require intervention; otherwise, path dependency becomes more likely. Blockchain-based technologies require impact measurement as a tool to evaluate their success. 4) Intention and potential orientation offers a useful approach to evaluate weaknesses of a technology design. 5) The shaping process of blockchain-based technologies involves many different actors from programmers and companies to users, governments, and society. 6) Guiding principles for sustainable technologies can be a valuable approach to support the development blockchain-based technologies that foster sustainability.

This PhD project illuminates the supposed contradiction of blockchain technology – blockchain technology in the form of mining will destroy the world, while blockchain applications can save it. This supposed contradiction is, however, conditional. It only exists when PoW blockchains are used and the system is designed to address sustainability issues. If, instead, a non-PoW blockchain is applied for blockchain-based technologies that foster sustainability, this contradiction does not exist. It should further be highlighted that this PhD project investigated blockchain technology from a sustainability perspective. Other important perspectives, such as the performance of different consensus mechanisms from a computer science perspective, are not included. However, environmental costs should also be considered when evaluating such technologies.

8.1. CONTRIBUTION AND IMPACT

This PhD project contributes in several ways to improving the current understanding of environmental impacts of blockchain technology, LCA of emerging technologies, and blockchain-based technologies in supply chains.

Article I is the first – and still the only, to the author's best knowledge – reproducible LCA of Bitcoin mining. It is the first study that uses an established methodology to assess Bitcoin mining's environmental impact, as previous – and current – studies use ad hoc approaches and do not build on established frameworks. This PhD project introduced a life cycle perspective to Bitcoin mining. Hotspots throughout the life cycle and within specific parameters (e.g. locations) were identified. Uncertainty and sensitivity analyses were conducted revealing which parameters are particularly sensitive to changes in demand.

The PhD project also addressed the nonlinearity of scaling up emerging technologies such as Bitcoin. It illustrated that uncertainties related to the Bitcoin network (e.g. regulations, price development, scaling the technology, consumer behavior) are substantial and make it difficult to develop even short-term predictions, let alone long-term ones. While LCA is a more advanced tool to assess environmental impacts compared to approaches taken in previous studies, this PhD project has also shown some of its limitations in the context of assessing Bitcoin mining. The LCA model was unable to account for short-term volatility and the abovementioned uncertainties, demonstrating that LCA has its limitations as a stand-alone tool to address prospective technology assessments in such volatile and uncertain environments.

This PhD project has also contributed to raising awareness about the impacts of Bitcoin, PoW blockchain, and blockchains in general. Due to the wide-ranging coverage of Article I, I was contacted by many journalists, events, and students (cf. dissemination for an overview of activities). Conducting an LCA provided an entry point for people who understood LCA and environmental impacts but were new to the topic of Bitcoin and blockchains. I explained to journalists what we know about the environmental impacts of different blockchains and blockchain applications and noted areas in which additional research is needed. I also presented a sustainability research perspective at panel events with over 100 guests, and I was interviewed for student projects on similar topics.

The PhD project further contributed to existing research on blockchain technology applied to supply chains, particularly from a sustainability perspective. The project highlighted that blockchain is one component of a system of technologies rather than a stand-alone technology. This systemic perspective was previously lacking in research on this topic. Through this perspective, the project contributed to the discussion on whether the impact of a single component (e.g. blockchain technology) can be separated from the impact of the entire system. While most of the existing research focuses on the potentials of blockchain technology or specific implementations, the PhD project instead developed a middle-range theory on how blockchain-based technologies in supply chains can create positive social and environmental impacts. This theory arose from conversations with experts with different roles in supply chains who have seen the actual implementation of blockchain-based technologies. The PhD project further exemplified four specific pathways for impact creation. The middle-range theory should be further tested and adjusted, but it can assist stakeholders in understanding how blockchain-based technologies can be used to generate positive impacts.

Additionally, the PhD project identified a lack of impact measurement in many blockchain-based technology implementations. This is concerning because – in line with project-based prospective technology assessment – changes can easily be made early, but if no measurements of success (e.g. impact) exist, it may be difficult to determine what changes are needed. The PhD also investigated the relationship between blockchain-based technologies used as a mechanism to govern sustainability in supply chains and established voluntary sustainability standards. This investigation confirmed that blockchain-based technologies are a system of technology, and such systems can vary significantly in terms of both their technology design and intentions. Hence, different relationships to existing governing mechanisms can be possible.

The PhD project assessed multiple projects and involved different stakeholders and their perspectives. This approach moved beyond conceptual studies showing the theoretical potentials of the technology to enable the assessment of real implementations and their implications. The study participants for Article IV represented multiple perspectives and profiles of the stakeholders for blockchain-based technologies implemented in the supply chain, ranging from representatives of technology providers to brands and producers from different countries. Engaging a diverse representation of actors to learn from their experiences was considered particularly important. The findings from the PhD project will be shared with the study participants and potentially inform their future developments.

8.2. RECOMMENDATIONS FOR FUTURE RESEARCH

Despite the advancements made in this PhD project, the need for further research on sustainability and blockchain technology remains. Several recommendations for such future research are provided here.

First, future studies should focus on achieving a better understanding of the mechanisms by which different blockchains (PoW and non-PoW) consume energy and their short-term dynamics, in particular how energy consumption relates to price spikes. This research should include the entire blockchain network rather than solely focusing on mining. To increase the geographical accuracy of mining locations in the models used for such assessments experts should be involved through interviews and surveys. The inclusion of industry data will be particularly important for the discussion of renewable energy uses in mining. Understanding the market dynamics (e.g. the volatility of market prices) and how these affect energy consumption also requires further investigation. Moreover, meaningful comparisons should be carried out. For example, a comparative LCA of different blockchain networks or a comparison between cryptocurrencies and fiat currencies could be conducted, although a fitting functional unit needs to be found in the latter case.

The PhD project has also illustrated the limitations of LCA's ability to help researchers develop long-term predictions of Bitcoin mining. Therefore, LCA must be supported by other approaches to be useful in the prospective technology assessment of Bitcoin mining – a volatile and uncertain emerging technology. For example, experts from different fields could be recruited to develop scenarios exploring the different development trajectories of Bitcoin and other cryptocurrencies. A variety of experts would be needed for this to address the uncertainty regarding market development, technological development, regulation, and consumer uptake, among others.

Furthermore, this PhD project can serve as a baseline for later studies, as more long-term studies are needed that investigate specific blockchain-based technology implementations over long periods and test and adapt the middle-range theory and impact pathways proposed in Article IV. For this, only future research adopting a long-term perspective will be able to fully confirm whether the outcomes and impacts identified in this PhD project will be realized over time. This extended time frame should be taken into consideration for future research.

Furthermore, the relationship of blockchain-based technologies to existing solutions such as voluntary sustainability standards should be investigated more, applying a long-term perspective. It is possible that most projects analyzed during this PhD project currently fit within the co-existing relationship category, but this could change over time as projects become more mature.

Additionally, projects need to start measuring their impacts. Project-level impact measurements would not only be valuable for testing and refining the middle-range theory but could also be used to conduct a prospective technology assessment of the system of technologies at the project level, as well as to learn about blockchain-based technology projects and evaluate their success.

While this PhD project has significantly contributed towards better understanding blockchain technology from a sustainability perspective, there is still much to be investigated. However, one thing is clear. Environmental and social impacts – positive as well as negative ones – should be considered when evaluating blockchain technologies. Ultimately, only the future will tell us whether blockchain technology will foster sustainability or will only be remembered for its hype to do so.

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Life Cycle Assessment of Bitcoin Mining

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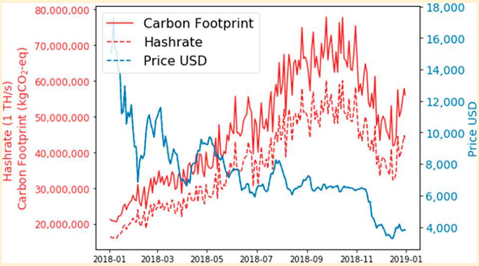
Supporting Information

ABSTRACT: This study estimates the environmental impact of mining Bitcoin, the most well-known blockchain-based cryptocurrency, and contributes to the discussion on the technology's supposedly large energy consumption and carbon footprint. The lack of a robust methodological framework and of accurate data on key factors determining Bitcoin's impact have so far been the main obstacles in such an assessment. This study applied the well-established Life Cycle Assessment methodology to an in-depth analysis of drivers of past and future environmental impacts of the Bitcoin mining network. It was found that, in 2018, the Bitcoin network consumed 31.29 TWh with a carbon footprint of 17.29 $MtCO_2$-eq, an estimate that is in the lower end of the range of results from previous studies. The main drivers of such impact were found to be the geographical distribution of miners and the efficiency of the mining equipment. In contrast to previous studies, it was found that the service life, production, and end-of-life of such equipment had only a minor contribution to the total impact, and that while the overall hashrate is expected to increase, the energy consumption and environmental footprint per TH mined is expected to decrease.



INTRODUCTION

Today, there are many expectations that blockchain technology will change the world for the better.[1−6] The technology is, in extreme synthesis, a distributed ledger that removes the middlemen and establishes trust between unknown parties.[2] Currently, the most mature implementations of blockchain are in the financial sector[7] with the cryptocurrency Bitcoin being a prominent example.[8,9]

While in traditional finance, banks act as a trusted authority and keep track of transactions and balances, in the Bitcoin network, the entire memory of transactions is stored digitally in "blocks" that are linked as a chain—hence blockchain—and kept by a network of peers. A consensus mechanism is how the peers in the Bitcoin network continuously agree on the order of newly added blocks and thus secure the data in a decentralized fashion. Bitcoin's consensus mechanism is based on a proof-of-work (PoW) approach where peers in a network compete in winning the right to add the next block to the chain, a process called "Bitcoin mining" that is performed by "miners". The miners compete in solving a puzzle, which requires substantial computational power. To do so the miners try to find a "nonce value", which is a random value. Every time the miners guess the nonce value an algorithm is applied that maps the data of their suggested block—including the guessed nonce value—−to a value of a fixed length. This output value is called a hash. A miner wins the right to add a new block when this hash is lower than a target value.[10] The target value of the puzzle is adjusted automatically so that, on average, only one block is mined every 10 min.[11] Thus, the more miners join the network or the more efficient miners become, the more difficult it becomes to mine a block, while the block generation time remains approximately constant. The hashrate corresponds to the number of hashes guessed per second. In 2018, the hashrate of the entire Bitcoin network ranged from around 15 to 60 million Tera hashes (TH) per second.[12]

With the increasing popularity of cryptocurrencies concerns were raised regarding the sustainability of Bitcoin, under the rationale that since the Bitcoin network uses a high amount of electricity for mining, its environmental impact might be substantial. A wide range of estimates of Bitcoin's energy consumption have been published in the media, reflecting the uncertainty of such assessments. For example, claiming that Bitcoin mining uses more energy than mining gold,[13] is equal to Switzerland's energy consumption,[14] was to use all the world's energy by 2020,[15] and be alone responsible for not reaching the Paris Agreement.[16] Recent studies—both in gray and academic literature—estimate the energy consumption of Bitcoin to be 22−67 TWh/yr (mid-March 2018),[17] 43 TWh/yr (October 2018),[18] 45 TWh/yr (November 2018),[19] 62 TWh/yr (average of 2018),[20] 39−83 TWh/yr (mid-November 2018),[21] and 105.82 TWh/yr (29 July 2018).[22]

Stoll et al. estimate the annual carbon emissions of Bitcoin between 22.0 and 22.9 $MtCO_2$ (November 2018).[19] Digiconomist proposes the estimate of 30.35 $MtCO_2/yr$[20] (average 2018). McCook[22] estimated the carbon footprint to

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be 63 $MtCO_2$/yr (July 2018). These numbers are contested by Bendiksen et al.[23] who estimate that 77.6% of Bitcoin mining is powered by renewables, while Rauchs et al.[21] report the share of renewables to be around 28%.

A common feature of the previously mentioned studies is that the assessment of environmental impacts is built on ad-hoc methods. For example, McCook[22] uses global emission factors only and Digiconomist[20] assumes 70% of miners to be located in China and the rest impact free. Despite the substantial uncertainties in the data and choices used in previous models, an explicit uncertainty assessment is lacking in previous studies. There is thus the need to use a solid methodological basis to increase the transparency, validity, and replicability of the environmental assessment of Bitcoin.

A well-established approach to assess environmental impact is Life Cycle Assessment (LCA).[24] LCA allows for a detailed analysis of a system including all stages from raw material extraction through production processes, use phase, and disposal or recycling.[25] Previous studies have used LCA to study different emerging technologies[26] from power generation,[27,28] electric vehicles,[29] resource recovery from e-waste,[30] to food processing.[31] The challenge of prospective analysis is that data gaps are substantial and need to be dealt with accordingly,[32] for example, by means of scenario development, or by applying techniques for sensitivity and uncertainty analysis.[32]

Summing up, previous studies assessing the impact of the Bitcoin mining network show contrasting and arguably overestimated results, and a key challenge in this assessment is the scarcity of accurate data on key factors determining the impact of the mining network. This study wants to bring new insights in this area by providing a more detailed analysis of the hotspots of environmental impact in the Bitcoin mining network and by increasing the accuracy in the modeling of regional electricity mixes. Furthermore, this study wants to add a prospective approach by considering how electricity generation or the geography of the mining network might change in the future. The added value of this analysis is adopting LCA as robust scientific methodology, the use of established databases for assessing environmental impact, including the impact of mining equipment in the analysis, and providing an outlook of future impacts.

METHODS AND MATERIALS

This study takes both a retrospective and a prospective approach, and two different system models were respectively used. The retrospective analysis was conducted via attributional LCA, the prospective one via consequential LCA.[33] The attributional model was used to determine environmental impacts of the Bitcoin network in 2018, whereas the consequential LCA to estimate the environmental consequences of an increase in Bitcoin mining in the future. The retrospective analysis only assesses the impacts for 2018, because the hashrate before 2018 was significantly lower, 17 million TH/s at its top,[12] and a historic analysis would require data on the location of miners and their mining equipment for every distinct period in the system, which is either not available or highly uncertain. Figure 1 shows the structure of the product system that was analyzed in both cases. The ecoinvent v3.5 database was used for background modeling, the allocation at the point of substitution (APOS) database for the retrospective model, and the consequential one for the prospective model.[34] The impact of such a system was determined in multiple midpoint impact categories[35] using the IPCC[36] and ReCiPe[37] methods. In the text, the IPCC method is reported for the carbon footprint. To understand the uncertainty associated with the background data, Monte Carlo simulations with 1000 iterations were carried out for the attributional baseline model and each consequential scenario.[38,39] All analyses were performed using the Brightway2 open source LCA software.[40] Results can be reproduced by using code available in a GitHub repository[41] so that the results are transparent and can easily be reproduced.

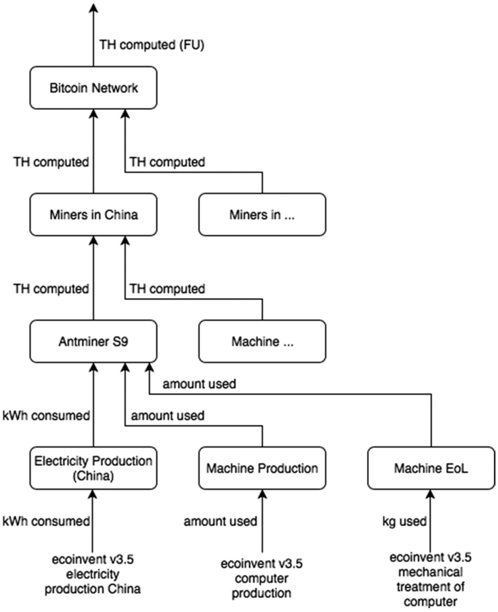

Figure 1. Structure of the product system under analysis. Boxes indicate activities in the foreground system. Arrows indicate exchanges. TH = tera hashes. FU = functional unit.

Functional Unit for the Attributional Model. The functional unit of the attributional model was defined as computing 1 TH. This choice was motivated by the fact that with a constantly changing hashrate, between 15 and 60 million TH/second in 2018 alone,[12] using a specific rate would not allow comparisons between studies that have been carried out at different points in time. Instead, the impact associated with computing 1 TH can then be linearly upscaled to obtain the impact of Bitcoin for a given period according to the actual hashrate, which can be determined using available data on the network's hashrate.[12]

Bitcoin Network in the Attributional Baseline Model. The information currently available on the location of Bitcoin miners is scarce and inaccurate. However, this information is crucial for estimating the environmental impact of the Bitcoin network, which is highly dependent on the electricity mix of the geographical locations where mining is performed. A geographical distribution of the Bitcoin mining network was developed in this study based on information available from two previous studies, Bendiksen et al.[23] and Rauchs et al.,[21] as well as own research on mining pools.[42] Details on the methodology used to derive this geographical distribution are provided in Supporting Information (SI) Section 2. Table 1 shows the geographical distribution of the miners used in the attributional baseline model for 2018.

Table 1. Geographic Distribution of Bitcoin Miners Used in the Attributional Baseline Model

location	share
China	53.5%
Inner Mongolia	12.3%
Xinjiang	10.7%
Sichuan	30.5%
Canada	12.8%
Quebec	4.0%
British Columbia	4.1%
Alberta	4.7%
U.S.	13.7%
New York state	7.5%
Washington state	6.2%
Iceland	4%
Georgia	4%
Norway	4%
Sweden	4%
Russia	4%

Mining Activities in the Attributional Baseline Model. Besides the energy mix, the electricity consumption of the Bitcoin network depends also on the equipment used for mining as it determines the efficiency of mining, namely the electricity consumption per TH computed. The types of equipment included in the model are taken from Bendiksen et al.[23] 79.9% of the miners modeled are Antminer S9, 7.6% Avalon 841, 6.7% Ebang E10, and the remaining 5.8% are modeled as other machines. Details on the methodology used to derive these values are provided in SI Section 4.

Mining Equipment in the Attributional Baseline Model. The use of mining equipment involves three main activities: electricity consumption, production, and end-of-life (EoL) of the equipment.

The main contributor to electricity consumption is the use of electricity for mining, determined according to the product specifications of each machine. Large facilities, especially in warmer climates, may require additional energy for cooling and other inefficiency. In the model, an additional electricity use of 5% was assumed based on Stoll et al.[19] The consumption of electricity was modeled using the electricity mix from the ecoinvent v3.5 APOS database of each country where the miners are located.[34]

The amount of equipment that is produced and hence needs to be disposed of is approximated using machine lifetime. According to Digiconomist,[43] Bitcoin mining equipment has an average lifetime of 1.5 years, a figure that was also used in this model. For the production of mining equipment, the ecoinvent v3.5 process for "market for desktop computer without screen" was chosen.[44] Since this data set refers to a computer with a weight of 11.3 kg and the mining equipment is much lighter (e.g., 4.2 kg for an Antminer S9), the amount used as input was corrected taking into account the weight difference (e.g., 4.2/11.3 kg desktop computer for the Antminer S9). Similarly, for the end-of-life of the machines, the ecoinvent v3.5. process "mechanical treatment of used desktop computer" for 1 kg of equipment was selected[45] and scaled to the weight of the mining equipment.

Sensitivity Analysis in the Attributional Baseline Model. A sensitivity analysis was carried out to identify how key modeling parameters and modeling assumptions affect the results.

First, the sensitivity to the electricity mix and geographical distribution of miners was investigated. Three different electricity mixes were modeled: 100% hydropower-based representing a best case; 100% coal-based representing a worse case; and a global average mix. Then, three divergent geographic distributions were modeled. The "Cambridge Centre for Alternative Finance" distribution—in short CCAF distribution—is based on Rauchs et al.[21] It is important to highlight that only 1.7 GW of the mining capacity has been captured in the study by Rauchs et al.,[21] and it is not limited to Bitcoin as mining activities of the four largest cryptocurrencies are included.[21] The "CoinShares" distribution is based on Bendiksen et al.[23] who identify major regions of Bitcoin mining and distribute the mining activities evenly among those areas. The "Mining Pools" distribution is based on information about the mining pools that successfully mined Bitcoin in 2018.[42] Details on the methodology used to derive each geographical distribution are provided in SI Section 2.

Next, the sensitivity of the baseline model with respect to other key parameters was tested. This allowed to understand the effect of improving mining efficiency or increasing electricity consumption. The sensitivity of the model results was tested with respect to (1) a 10% increase in energy consumption; (2) a 10% decrease in energy consumption; (3) a 10% increase in the hashrate of the mining equipment; (4) a 10% decrease in the hashrate of the mining equipment; and a change in the lifetime of the mining equipment to (5) 1 year and (6) 2 years.

Consequential Model. The consequential approach is fundamentally different from the attributional one as it focuses on quantifying the effect of an increase in the demand for mining. In the consequential LCA, three different scenarios were modeled.

The first model describes a business-as-usual (BAU) scenario that differs from the attributional baseline model only in the background system: the consequential version of the ecoinvent v3.5 database instead of the attributional (APOS) version.[34] This model describes a situation where the geographical distribution of miners is irresponsive to changes in demand for mining, but the surrounding energy system and electricity network is responsive to changes in demand for electricity.

The second model describes a technology-sensitive scenario where an increase in demand for mining will be met by installing new mining capacity and investing in the most efficient mining equipment. In other words, in this model only the marginal mining technologies are included.

The third model describes a location-sensitive scenario where an increase in demand for mining is met not only by installing efficient mining capacity, but also by changing the geographical distribution of the miners toward locations that allow for more competitive conditions (e.g., lower energy prices and temperatures).

Functional Unit of the Consequential Model. The functional unit of the consequential model was defined as increase in demand for computing 1 additional TH. The consequential model thus investigates the effect associated

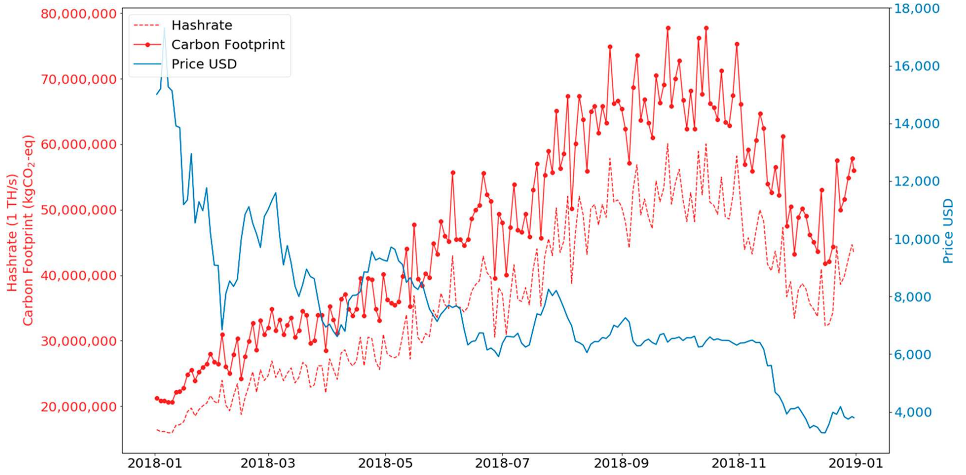

Figure 2. Carbon footprint of Bitcoin in 2018 compared to the market price and the hashrate.

with a marginal increase in mining rather than the total absolute impact of the whole mining.

Bitcoin Network in the Consequential Model. In the BAU and technology scenarios, the same geographical distribution of miners was maintained as in the attributional baseline model (Table 1). In the location scenario, the geographical distribution was adjusted to only include locations where miners are opening new facilities. With a changing political environment in China,[46,47] miners are looking for new locations with cheap electricity, fast Internet, and low temperatures. According to Bendiksen et al.[23] as well as several media articles[48−52] new mining facilities have been opened in parts of Scandinavia, North America, and Russia. Thus, in the location scenario the miners were assumed to be equally distributed among Norway, Sweden, Iceland, Russia, Canada, and the U.S.

Mining Activities in the Consequential Model. In the BAU scenario, the same mining equipment as in the attributional model was used, which has an overall efficiency of 0.095 J/GH. In the technology and location scenarios the model includes only the most efficient mining equipment currently on the market. No data is available on how the share of different types of mining equipment has changed over time so this modeling relies heavily on the Authors' assumptions, and should be therefore taken as an explorative scenario exercise. It was assumed that the marginal mix of mining equipment would be composed of 70% of Antminer S15, 20% of Ebang E11++, and 10% of Avalon 1041. With this distribution of mining equipment an overall efficiency of 0.0545 J/GH is reached, which is 42.6% more efficient then the mining equipment of the BAU scenario.

Mining Equipment in the Consequential Model. Regarding additional electricity for cooling and other inefficiency as well as the lifetime of mining equipment, all three consequential scenarios maintain the same assumptions as in the attributional baseline model. In contrast to the attributional model, all three consequential scenarios are linked to the ecoinvent v3.5 consequential database.[34]

■ RESULTS AND DISCUSSION

In the attributional baseline model, the energy consumption for every TH mined is 27.14 mWh. That means that the Bitcoin network consumed 31.29 TWh in 2018. As expected this value is consistent with previous studies (22−67 TWh/yr,[17] 45 TWh/yr,[19] 62 TWh/yr,[20] 39−83 TWh/yr,[21] 105.82 TWh/yr[22]) given the similar assumptions. Deviations from previous studies are due to the fact that, for example, de Vries,[17] Stoll et al.,[19] and McCook[22] calculate their results based on one hashrate value only (the hashrate measured on the day their analysis was performed) instead of calculating the total amount of hashes actually mined in a year. The study by McCook[22] further uses different assumptions regarding the production of mining equipment and from the documentation available it is not entirely clear how his calculations were done.

The mining of each TH produced 15 mgCO_2-eq (coefficient of variation CV = 1.30). For 2018, this makes a total of 17.29 MtCO_2-eq This value is lower than what was reported in previous studies: 22 to 22.9 MtCO_2-eq,[19] 30.35 MtCO_2-eq,[20] and 63 MtCO_2-eq.[22] The difference in results is in part due to the fact that the studies already differ with respect to the network's energy consumption. Additionally, the methods of calculating the carbon footprint deviate. Stoll et al. use the average emission factors of power generation in each country and multiply that with the power consumption in that region.[19] Digiconomist assumes that 70% of miners are located in China and the remaining 30% are renewable energies with zero carbon footprint. Thus, Digiconomist takes average emission factor of the Chinese grid and multiplies it by 0.7.[20] Finally, McCook uses the global electricity mix and energy source specific emission factors to calculate the carbon footprint.[22]

Figure 2 displays the carbon footprint of the Bitcoin network in 2018 together with the hashrate and the Bitcoin price in USD. The curves for the hashrate and the carbon footprint are directly proportional as the same impact factor is applied for the entire year (i.e., model parameters are kept constant).

The hashrate reflects the size of the Bitcoin network, of how many miners are trying to gain the right to add the next block. However, the hashrate does not reflect the market price or the

Table 2. Environmental Impact of 1 TH in the Attributional Baseline Model and All Three Consequential Scenarios According to the IPCC and the ReCiPe Methods

impact category	attributional baseline model	BAU consequential scenario	technology consequential scenario	location consequential scenario
climate change GWP (mgCO_2-eq), IPCC	15.0	13.3	7.74	3.20
climate change GWP (mgCO_2-eq), ReCiPe	14.7	13.1	7.59	3.17
fossil depletion FDP (MJ)	3.74×10^{-06}	3.72×10^{-06}	2.16×10^{-06}	1.15×10^{-06}
metal depletion MDP (kg)	3.36×10^{-07}	6.50×10^{-07}	3.86×10^{-07}	3.65×10^{-07}
human toxicity HTP (kg 1,4-DCB-eq)	5.65×10^{-06}	5.61×10^{-06}	3.34×10^{-06}	3.05×10^{-06}
terrestrial acidification (kg SO_2-eq)	6.04×10^{-08}	3.20×10^{-08}	1.67×10^{-08}	6.87×10^{-11}
freshwater eutrophication (kg P-eq)	6.59×10^{-09}	4.63×10^{-09}	2.73×10^{-09}	2.40×10^{-09}
photochemical oxidation formation POFP (kg ethylene-eq)	4.24×10^{-08}	3.47×10^{-08}	2.00×10^{-08}	5.88×10^{-09}
ozone depletion ODP (kg CFC-11-eq)	4.74×10^{-13}	4.88×10^{-13}	2.83×10^{-13}	3.50×10^{-13}
terrestrial ecotoxicity (kg 1,4-DCB-eq)	7.16×10^{-10}	9.81×10^{-10}	5.74×10^{-10}	4.06×10^{-10}
marine ecotoxicity (kg 1,4-DCB-eq)	3.06×10^{-07}	5.01×10^{-07}	2.92×10^{-07}	3.30×10^{-07}
freshwater ecotoxicity (kg 1,4-DCB-eq)	3.43×10^{-07}	5.72×10^{-07}	3.33×10^{-07}	3.77×10^{-07}

amount of transaction throughput meaning it can—in the short term—increase or decrease independently of both the market price and the transaction throughput.

Table 2 displays the results for computing 1 TH for all the midpoint impact categories considered in this study. McCook[22] also calculates values for eutrophication, acidification, and ecotoxicity based on the global electricity mix. However, the limited documentation provided by McCook[22] on the methodology used does not allow making a comparison with the results of this study.

Hotspot Analysis. A contribution analysis showed that the use phase is the major contributor to carbon footprint with 99.043%. Equipment production and EoL only contribute 0.932% and 0.025%, respectively.

Table 3 shows that four locations alone contribute more than 70% to the total carbon footprint of Bitcoin mining. The table also shows that the share of carbon footprint is larger than the share in mining for a number of locations including Inner Mongolia, Alberta, and Russia. Other locations such as Quebec, Iceland or Sichuan show only a minor individual contribution to the total carbon footprint. This is due to less carbon intensive electricity mixes in these regions. Therefore, installing new mining facilities in those locations, would lead to a decrease in the carbon footprint per TH.

Table 3. Contribution to the Carbon Footprint by Location

location	share in mining	contribution to carbon footprint
Inner Mongolia, China	12.3%	26.2%
Xinjiang, China	10.7%	16.5%
Alberta, Canada	4.7%	16.5%
Russia	4.0%	13.6%
Washington state	6.2%	8.7%
New York state	7.5%	5.4%
Sichuan, China	30.5%	4.6%
Georgia	4.0%	3.2%
British Columbia, Canada	4.1%	2.0%
Iceland	4.0%	1.2%
Sweden	4.0%	1.0%
Norway	4.0%	0.6%
Quebec, Canada	4.0%	0.5%

Looking at the contribution by equipment type, the equipment used in the attributional baseline model contributes to a similar share to mining and to the carbon footprint. For example, the Bitmain Antminer S9 makes up 79.9% of the mining equipment, and contributes 80.7% to the total carbon footprint.

Sensitivity Analysis. The influence of changes in electricity mix on the environmental impact is substantial. Figure 3 shows the results of the sensitivity analysis considering the three different electricity mixes and three different geographical distributions.

The main differences between the three different geographical distributions is largely explained by the different assumptions used in modeling the Chinese miners. The CCAF distribution assumes that 23.2% of miners are located in China,[21] while the attributional baseline model assumes 53.3%, the CoinShares assume 60%,[23] and the Mining Pool model assumes 77.3%. The CoinShares model assumes further that the majority of miners are located in Sichuan, China,[23] where 77% of the electricity is produced from hydropower.[53] It was not possible to estimate shares for locations within Chinese provinces, Canadian provinces, and U.S. states in the Mining Pool model. The fact that the Mining Pool model shows a 71% higher carbon footprint than the attributional baseline model indicates not only the significant impact of mining locations, but also the importance of using accurate information about the geographical location of miners and the electricity mix in such locations. The average electricity mix in China has a different impact than the average mix in Sichuan province, China. On average, 1MJ in China produces 0.313 kg of CO_2-eq, while 1MJ in Sichuan province produces only 0.0974 kg of CO_2-eq according to ecoinvent data.[53,54]

A decrease and increase of 10% of electricity consumption—that could for example, be caused by a change in miner efficiency or cooling requirements—result, respectively, in a decrease and increase of 9.9% of the carbon footprint. The amount of cooling required for Bitcoin mining varies depending on climate, scale of mining facility, and mining equipment used.

A decrease and increase in the hashrate by 10% led to an increase and decrease of 10% of the carbon footprint, respectively. Improving the efficiency of mining equipment is likely to reduce the impact per TH.

A decrease in lifetime of the mining equipment from 1.5 to 1 year led to a minor increase of the carbon footprint by 0.48%,

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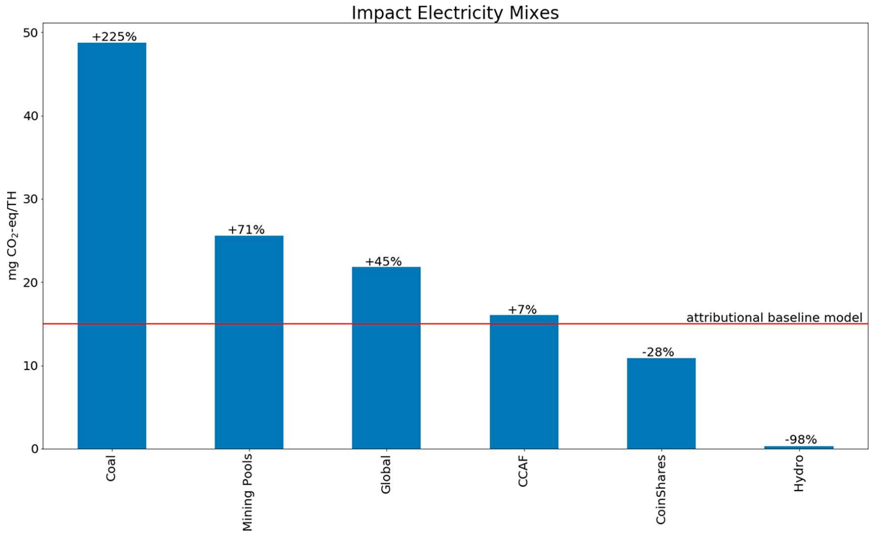

Figure 3. Carbon footprint in mgCO_2-eq per TH of the Bitcoin network in 2018 with different electricity mixes and geographical distributions.

whereas an increase to 2 years led to a small decrease of 0.24%. The effect of the lifetime of mining equipment on the carbon footprint is negligible, since the equipment production phase contributes less than 1% to the overall carbon footprint and the use phase—the mining—is highly energy intensive.

Consequential Model and Future Scenarios. While the attributional model answered the question on what was the past impact of the Bitcoin mining network under specific assumptions, the consequential models answer the question of how the carbon footprint would change by increasing the computing demand. Table 2 displays the impact of mining one additional TH for all the midpoint categories considered.

In the BAU scenario, the impact of increasing the demand by one TH results in an impact of 13.3 mgCO_2-eq per TH (CV = 0.99). The underlying model assumes that an increase in demand for electricity will be met by the marginal suppliers of electricity in each country.

The carbon footprint of mining one additional TH in the technology scenario assuming more efficient mining equipment was 7.74 mgCO_2-eq/TH (CV = 0.54), which is 42% less than in the BAU scenario.

Mining one additional TH in the location scenario leads to a carbon footprint of 3.20 mgCO_2-eq/TH (CV = 0.15), which is a 76% improvement to the BAU scenario. Compared to the previous two scenarios the impact categories ozone depletion, marine ecotoxicity and freshwater ecotoxicity increase slightly (see Table 2). This shows that while the carbon footprint in the new locations decreases, renewable energies have higher impacts in other categories.

Additional Relevant Aspects on Bitcoin Mining and Outlook. This study showed that the location of the miners has the highest impact on the environmental impact of the Bitcoin network. Miners will move to locations where electricity prices are very low. Locations with very low electricity prices include those with unused electricity from hydropower (e.g., Sichuan), but also places that use cheap electricity from coal (e.g., Inner Mongolia). The case of Plattsburg (New York) constitutes a recent example of how miners flocking to a city with cheap electricity can increase its energy consumption to the point where the city is no longer able to provide cheap electricity and has to import it from elsewhere.[55] In cases like this, the miners only shift the environmental impact to other users. One way to make sure that Bitcoin mining is truly sustainable would be if the miners established new capacity of renewable energy production ensuring that the marginal electricity consumption is environmentally friendly.

One important challenge in the making of this study was the lack of reliable data sources. Many references listed in this study come from news outlets and grey literature. While Bitcoin has gained a lot of attention in popular media, the academic literature on Bitcoin mining is scarce. Furthermore, the data in peer-reviewed literature is outdated[56,57] considering that in the past couple of months the Bitcoin network has grown substantially (see Figure 2) and any data before late 2017 analyzed a much smaller system than the present one.[12] Therefore, several assumptions such as mining locations and equipment used in this study have been based on gray literature and supported by the Authors' own reflections and assumptions. Due to this scarce and diverging data basis it is important to highlight that this analysis and its results are characterized by an intrinsic uncertainty. Carrying out sensitivity analyses for all parameters was a way to make this uncertainty explicit and to provide an insight on the range of possible outcomes. Further research should focus on a more solid base of data regarding miner location, and mining equipment used. This could be done using both expert interviews and a survey among the miners. Since these two parameters are major influencer of environmental impact, using even more accurate data would substantially decrease model uncertainties.

Another possible way to increase the accuracy of the model is to consider the Bitcoin network as a whole and not focus on Bitcoin mining only. Such research should include impacts related to nonmining nodes and the growing number of off-chain transactions. The inclusion of these factors was not coherent with the proposed model and therefore outside the scope of this study. A simple estimation of the lower bound of the energy consumption related to nonmining nodes carried out during this study showed that in 2018 nonmining nodes consumed 0.2 GWh, which is very small compared to the energy consumption of mining. Details on the calculation used to derive this energy consumption is provided in SI Section 6. Uncertainty of this calculation is high, though, as changing the assumptions regarding the computers used by the nodes could lead to a much higher impact, and this uncertainty should be addressed in future research.

This analysis of the Bitcoin mining network contributes with a strictly technical perspective to the broader discussion on the sustainability of the international cryptocurrency. The results should be considered in the larger context of a borderless currency that is difficult to regulate and where political and economic concerns play as important a role as technical and environmental ones. Bitcoin is not only difficult to regulate because it is a global currency, but also because of its governance structure. Any changes of protocol would have to be proposed by developers and then be supported by a sufficient number of miners and users[11] involving a large number of people in the process. Therefore, it is important to remember socio-political aspects, but any discussion concerning regulation should be founded on a technical understanding.

This analysis of the Bitcoin network is not transferable to all applications of blockchain but is limited to the Bitcoin PoW blockchain. The environmental impact of different kinds of blockchains that use a consensus mechanism other than PoW, such as proof-of-stake (PoS), can be expected to be much lower since no electricity-intensive mining is necessary. In order to add a new block in PoS, users who stake a certain amount of cryptocurrency are randomly selected.[1] Thus, no mining is required.

This study further adds a forward-looking perspective. The consequential model helps understanding the environmental impacts associated with future developments of the Bitcoin network. The hashrate of the network is expected to continue growing. For example McCook[22] estimates this growth to be around 5.3% per year. Growing mining efficiency is likely to increase the overall hashrate as a lower electricity consumption per TH means lower electricity costs for the miners. However, in the long term, the hashrate might stagnate as network security reaches a satisfactory level and rates of return for miners might decrease with the shift from Bitcoin rewards to transaction fees as the primary income.[17,57] Modeling these synergistic effects was outside the scope of the current study and should ideally be the subject of future research.

Compared to previous studies on the same topic, this analysis was based on LCA as an established methodology to assess environmental impact and allows an analysis of specific contributors to Bitcoin's environmental impact as well as a prospective assessment. The results of this technical analysis are intended to support stakeholders in the Bitcoin community to assess the severity of Bitcoin's environmental impact, and is expected to contribute in a broader discussion on the future of mining that should inevitably also include social and economic aspects, thus supporting decision-makers in the domain of PoW-based cryptocurrencies.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.9b05687.

> Annual energy consumption and carbon footprint by Digiconomist (Section 1); determination of location of miners (Section 2); electricity mixes (Section 3); mining equipment shares and specifications (Section 4); impact assessment (Section 5); and energy consumption of full nodes (Section 6) (PDF)
>
> Online repository[41] with the code for the open source Brightway2 softwar; the model inventories are.csv-files that can be uploaded into the respective python scripts available in the online repository in order to reproduce the results. There is one script for the attributional (retrospective) models and one script for the consequential (prospective) scenarios (ZIP)

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The authors declare no competing financial interest.

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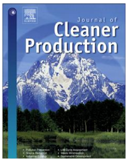

Technology assessment of blockchain-based technologies in the food supply chain

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A B S T R A C T

Beyond the financial domain, the application of blockchain is highly relevant in supply chain traceability, but the trade-offs between implementation challenges and achievable impact remain unclear. In this study, six cases of blockchain-based technologies in the food supply chain were analyzed applying a technology assessment framework that distinguishes between four different components of a technology: technique, knowledge, organization, and product. The study intends to provide new critical insights on how blockchain-based technologies can be implemented in the food supply chain and to further the discussion of social and environmental implications of blockchain-based technologies. The results highlight how blockchain is not a stand-alone-technology, but rather one element in a system of technologies. While blockchain-based technologies are expected to bring a variety of impacts, only some are directly attributable to the blockchain element: increased transparency, traceability, and trust. Other impacts such as improved data management are a side-effect of digitizing non-digital processes. Further research is needed to confirm whether blockchain-based technologies bring the expected sustainability improvements in food supply chains.

1. Introduction

Many modern supply chains spread over several countries and involve multiple actors making it increasingly difficult to know where a specific product comes from and how it has been produced. Companies have often little or no information about their second and third tier suppliers (Abeyratne and Monfared, 2016). This can be an issue when it comes to sharing information with consumers and guaranteeing the authenticity of a product. While supply chains have become more and more complex, consumers demand more information on product safety, quality, and sustainability (Behnk and Janssen, 2019). This is particularly the case in the food industry. A survey from 2016 found that 94% of consumers find transparency about how their food has been produced important (Astill et al., 2019). At the same time, consumer trust in food labels has been shaken in the light of food adulteration and mislabeling ranging from deliberate substitution, dilution, counterfeiting, misrepresentation of food, ingredients or packaging to false or misleading statements about the product. This costs an estimated $30 to $40 billion annually (World Economic Forum, 2019). A Canadian study from 2018 found that 44% of 382 seafood products sampled were mislabeled (Oceana Canada, 2018). Other major food adulteration problems came to light, when in 2013 horse meat was found in multiple ground beef products in Europe (Astill et al., 2019) or when in 2015 Chinese authorities seized 100,000 tones of expired meat (World Economic Forum, 2019). Thus, there is an increasing need for transparency of and trust in food supply chain information. One way to address this need is by reducing distances and the number of intermediaries between producers and consumers allowing increased traceability and trust through simplifying the supply chain. These supply chains are known as short food supply chains (Sellitto et al., 2018). Additionally, an interest in blockchain-based technologies to provide verified supply chain information and grant all stakeholders access to this information has emerged in order to help solve the traceability and trust problems through the use of technology (Kouhizadeh and Sarkis, 2018; Pearson et al., 2019).

In 2008, an unknown person or group under the name Satoshi Nakamoto, published a whitepaper describing the cryptocurrency Bitcoin (Antonopoulos, 2014; Nakamoto, 2008), of which blockchain technology is a key element. In short, blockchain is a data structure used to generate an add-only digital ledger that is kept in a decentralized manner by a network of peers, making it virtually impossible to alter. Blockchain-based technologies use blockchain to verify data and in some cases as a data storage. They are expected to become an

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innovative and disruptive force in the future, and some claim these technologies have a great potential to foster sustainable development (França et al., 2020). Blockchain-based technologies are appealing because they should allow for secure, robust, and trustworthy solutions, and bring improvements compared to current technologies or management systems in terms of transparency and traceability (George et al., 2019; Liu et al., 2019). According to Schmidt and Wagner (2019) the use of blockchain-based technologies should limit opportunistic behavior as well as the impact of uncertainty related to potential regulatory, political, economic or behavioral changes. Blockchain-based technologies can be employed in various industries outside of finance including in supply chain management, where they are expected to grow annually by 87% and increase from $45 million in 2018 to over $3300 million by 2023 (Chang et al., 2019a). For example, the company PepsiCo identified in their blockchain trial a 28% improvement in supply chain efficiency (Coindesk, 2019). A Walmart pilot with mangos has shown that with blockchain-based technologies the origin of products can be determined in just over 2 s, while it would have taken almost a week with current procedures (Wong et al., 2019).

Previous studies have reviewed blockchain-based technologies, including those in the food supply chain (Galvez et al., 2018; Kamilaris et al., 2019; Zhao et al., 2019). These studies describe blockchain-based technologies at various implementation levels and identify the advantages and drawbacks of their introduction in the supply chain. These studies generally identify ‘blockchain’ as a technology *per se*, while a clear decomposition of the elements of blockchain-based technologies in a systemic perspective is missing. Thus, the key role of blockchain is not clearly separated from the role of other elements – and this makes it difficult to understand what its real impact is. Therefore, the research gap this study aims to bridge is the lack of systemic understanding of blockchain-based technologies. Further, bridging this gap should allow to advance the discussion of what the social and environmental impacts of blockchain-based technologies are, a discussion that as noted by both Kumar et al. (2019) and Schmidt and Wagner (2019) remains today open and unresolved.

The study proposes a technology assessment of chosen cases that implement blockchain-based technologies in the food supply chain. In the assessment, blockchain-based technologies are considered a system of elements, one of which is blockchain. In particular, the study intends to answer the explorative research question of *How can blockchain be implemented in the food supply chain from a systemic perspective?* Previous research has shown that blockchain-based technologies can be implemented in different configurations, differing from the type of blockchain used to what tracking technology it is combined with (Francisco and Swanson, 2018; Tönnissen and Teuteberg, 2019). The issue is then to understand what combinations of different elements are used when implementing blockchain-based technologies in the food supply chain, what are their differences and similarities, and what are the consequences of implementing blockchain-based technologies in different configurations. This article aims at building a better understanding of the role of blockchain in blockchain-based technologies implemented in the food supply chain, building a foundation for further analyses, and furthering the discussion of social and environmental implications of blockchain in the field of supply chain traceability.

2. Material and methods

Qualitative research using concrete cases was conducted for this study: multiple examples of blockchain-based technologies implemented in food supply chains have been selected and analyzed by applying a technology assessment framework.

The cases for the comparative analysis were selected based on a set of pre-defined criteria. The criteria were defined in such a way that only those with a similar focus and maturity were analyzed. The idea was not to analyze concepts, but real-life examples of blockchain being implemented in a supply chain. The cases were selected based on the following criteria: use of blockchain in food supply chains, a traceability focus, sufficiently available information about how the technology is implemented, at minimum the completion of a pilot, and a sustainability focus of the case.

The cases were identified via web-search, networking with stakeholders in the blockchain community, subscriptions to various blockchain-related newsletters, and searching the database PositiveBlockchain.io (2019). In total, six cases were found to match the selection criteria, which is in line with Rowley (2002) according to whom 6–10 cases are typical. The chosen case studies focus on different food products including tuna, coffee, and eggs. An overview of the selected cases is shown in Table 1.

A simple technology assessment framework was used, based on Müller (2011). According to this framework, any technology is composed of four inseparable components: *knowledge, organization, technique,* and *product*. Fig. 1, reproduced from Müller (2011), shows this concept of technology. The four components can be analyzed separately but should be considered together when assessing technological change since a change in one component will lead to a change in the others (Müller, 2011).

Technique refers to all physical implementations involved in the technical process (Müller, 2011). This includes raw materials, components, and energy inputs that are transformed or consumed in the process. In the case of blockchain-based technologies in the food supply chain, this includes among other things software, decentralized platforms, tags, and tracking devices. *Knowledge* relates to empirically acquired skills, tacit knowledge and intuition of the producers and the scientific insight and creativity of the designers (Müller, 2011). This refers to the knowledge required for all actors involved in the implementation of blockchain-based technologies in the food supply chain. The *organization* component is the internal division of labor and pattern of specialization (Müller, 2011). Additionally, management and coordination processes are involved. In the supply chains, many different actors in varying constellations are involved. The *product* component is the immediate results of the combination of the first three processes. A distinction between material objects and immaterial services can be made (Müller, 2011).

The six cases have been analyzed according to these four components. This was done by studying whitepapers and reports as well as by validating the preliminary findings with three out of six of the organizations and companies developing the technologies. Table 1 provides an overview of the material used for the analysis.

In order to assure high validity and reliability of the study design and its results, several tests have been conducted, in line with the recommendations by Riege (2003) to ensure rigor in explorative case study research under a realist paradigm. First, construct validity was tested by allowing relevant representatives of each case to review the information related to their case. Internal validity was checked by conducting within-case analysis first, then doing cross-case pattern matching. External validity was provided by defining the scope as well as the boundaries of reasonable generalizations made in this study. Finally, reliability was assured by developing a case study database that provides an overview of the technology assessment according to Müller (2011) for each case.

3. Results

In this section, the results of the technology assessment of all six cases are compared. Similarities and differences are highlighted.

Table 1
Overview of the cases compared.

Company	Product	Short description	Documentation available
FairChain	coffee, chocolate	"Based on the concept of radical transparency and equal partnerships [FairChain uses] cutting edge technologies to stimulate and support business models that contribute to a truly fair distribution of the wealth across all participants in the value chain." (FairChain, 2020)	whitepaper, news coverage, personal contact
IBM Food Trust	foodstuffs(e.g. mangos)	"IBM Food Trust™ is a collaborative network […] enhancing visibility and accountability across the food supply chain. Built on IBM Blockchain, this solution connects participants through a permissioned, immutable and shared record of food provenance, transaction data, processing details, and more." (IBM, 2020)	homepage, news coverage, webinar
OpenSC	fish	OpenSC aims "to drive increased responsible production and consumption through supply chain traceability and transparency technology". (OpenSC, 2020)	homepage, news coverage
Provenance	tuna	Provenance enables "great brands to communicate the origin and impact of their products. Increase engagement by connecting to shoppers' changing values and help build a better world." (Provenance, 2020)	homepage, whitepaper, webinar
TE-FOOD	meat and eggs	"TE-FOOD is a successful farm-to-table livestock and fresh food traceability solution, focusing on emerging markets." (TE-Food, 2017)	whitepaper, e-mail contact
WWF pilot	tuna	The "WWF-led pilot [set out] to prove blockchain supply chain traceability for use in seafood traceability, specifically for tuna caught in a Fijian longline fishery." (Cook, 2018)	report, e-mail contact

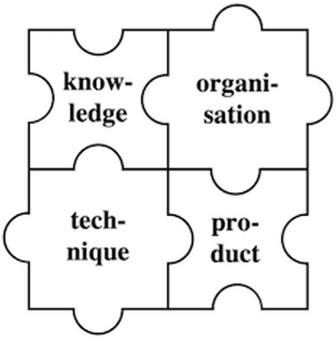


Fig. 1. Technology assessment scheme (reproduced from Müller, 2011).

Details for each case can be found in Table 2 and Appendix A, an excel file, which describes each case in a separate row with the columns showing information about technique, knowledge, organization, product, and the sources associated with each case.

3.1. *Technique component*

The technique element can be divided into several parts: blockchain technology, tracking technology, data entry, data handling, data storage, data communication, and tokenized incentives (see Fig. 2).

In the cases, different kinds of blockchains have been implemented. Provenance, OpenSC and the WWF pilot are all built on the public Ethereum blockchain (Cook, 2018; Ledger Insights, 2019; Provenance, 2019; TraSeable, 2019), whereas TE-Food relies on a combination of public and private blockchains (TE-Food, 2019; TE-Food, 2017), and FairChain as well as IBM Food Trust use private blockchains built using Hyperledger Fabric (FairChain Foundation, 2019a; Hyperledger, 2019). On a purely public blockchain all transactions can be viewed by anyone. Combining both public and private blockchains allows for a more customized solution that addresses specific needs and wishes. For example, TE-FOOD uses the public blockchain for token transactions and the private one for traceability transactions (TE-Food, 2017). IBM Food Trust is built on Hyperledger Fabric, a private blockchain, where users are only able to view data they are permissioned to (Hyperledger Fabric, 2019; IBM Food Trust, 2019a). All blockchains rely on a peer-to-peer network to guarantee decentralization. They also work with smart contracts, which are software programs that automatically execute and enforce underlying agreements. When the conditions of a smart contract are fulfilled, they self-enforce contractual conditions such as payments or legal obligations thereby removing the need for trusted third parties (Prause, 2019). For example, scanning a barcode of a product with a registered device can initiate a smart contract that triggers the transfer of the asset and the payment instantly allowing transactions to take place faster and more secure. The setup of the blockchain influences both the system's transparency, customizability, and speed. A private blockchain, for example, can process more transactions per second due to fewer but authorized peers verifying them.

For tracking interchangeable goods like fish, coffee, or mangos, different tracking technologies are used. Connecting the physical product to the digital record is one of the main issues of blockchain-based technologies of interchangeable goods in the supply chain. Tracking technologies include RFID tags, QR codes (OpenSC, 2019a; TE-Food, 2017) and NFC tags (Cook, 2018; Provenance, 2016). RFID tags are prominent to use for tagging materials before processing, while QR codes are preferred for the end-product. NFC tags on the final products are considered more secure and convenient (Provenance, 2016). TE-Food uses plastic security seals (1D/2D barcodes), label stickers (2D barcodes), printed paper bags (2D barcodes), or TE-Food scale labels (2D barcodes) for their final products (TE-Food, 2017). The kind of tracking technologies used influences the system's resilience against fraud and corruption as well as its costs. While QR codes are cheap, they are vulnerable to counterfeiting. NFC tags on the other hand are more secure, but also more expensive.

Data entry, one of the most vulnerable parts in a blockchain-based technology system, can be done in various ways. While the information on the blockchain is virtually immutable, it needs to be ensured that the data input is not manipulated. In the Provenance case, only fishermen who have been previously registered with a local NGO can enter a new catch. This is then done via text message that includes the GPS coordinates avoiding problems with internet connectivity on high sea (Provenance, 2016). In the WWF case, fishermen register their catch offline on a mobile device, which will be transmitted automatically when internet connectivity is available (Cook, 2018). FairChain's farmers need to be registered in order to enter a harvest. After completing the registration, they can sell their harvest at a harvest center where the coffee is sorted and weighted. The farmers then sign a contract with Moyee Coffee, FairChain's coffee retailer, that details among other points the price (FairChain Foundation, 2019a). In the OpenSC case, the vessel records the location of the catch. It is then verified by a machine learning algorithm and the GPS locations of the vessel that the catch has been made in legal fishing zones (OpenSC, 2019b).

Table 2
Overview of cases and components.

	Technique	Knowledge	Organization	Product
FairChain	• KrypC blockchain platform based on Hyperledger Fabric • QR codes for tracking • Data entry via webapp on phones (runs offline) • Off-chain database • QR code to access information • Digital ‘farmer wallet’ • token for consumers worth 0.25€	• Specific programming knowledge • Use of platform and app • How to initiate, transfer, and change an asset • Understanding of new token system (consumer) • Understanding digital wallets & payments (farmers)	• Brands: Moyee coffee & The other bar • KrypC • FairChain Foundation • NGOs • Farmers (currently 600) • Other supply chain actors • Consumer • Wageningen & Jimma University	• Management platform • QR code leading to product information and token
IBM Food Trust	• Hyperledger Fabric • RFID tags • Permission-based platform • Modular architecture • IBM cloud	• Specific programming knowledge • Use of platform in accordance with access rights • How to initiate, transfer, and change an asset	• Main organization, e.g. Walmart • IBM • Other supply chain actors • Consumers	• Platform for brand for desktop and mobile use • Depends on choice of modules implemented
OpenSC	• Both public and private blockchains • RFID tags, QR codes, NFC tags, and Bluetooth tags for tracking • GPS & machine learning model • Blockchain management platform • Installations in supermarket, website, apps, ecommerce sites, social channels	• Specific programming knowledge • Data science & marine science knowledge • Use of platform and app • How to initiate, transfer, and change an asset	• OpenSC • Data and marine scientists • Fishing company (Austral Fisheries) • Other supply chain actors • Restaurant, supermarket, etc. • Consumers • Certifiers • Audited by E&Y	• Management platform • Consumers access information by scanning QR codes, interactive installations, information for restaurant staff, online, websites, apps, ecommerce sites, social channels
Provenance	• Built on Ethereum • QR code & NFC tags for tracking • Initiate transaction on mobile phones for fishermen • Linking with ERP system • Smartphones, computers, & apps to access information	• Specific programming knowledge • How to initiate, transfer, and change an asset • Linking their own (ERP) systems to the blockchain • Using the blockchain explorer	• Provenance • Fishermen • Trusted local NGOs • Supplier • Factories • Auditors • Supermarkets, Restaurants & Fish dealers • Consumers	• Product information through scanning QR code or NFC tags • Open registry
TE-FOOD	• Both public (Ethereum) & private (Hyperledger) blockchains • QR code, plastic security seals, label sticker, RFID tags, printed paper bags, TE-Food scale labels • Off-chain data layer • App & terminals to access information • Token	• Specific programming knowledge • Development of guidebook and training of local representatives • Use of platform, app, terminal, etc. • How to initiate, transfer, and change an asset	• TE-FOOD • Farmers • Other supply chain actors • Consumers • Government/ authorities	• B2B mobile app (QR tools) • Self-service terminal • Customer app • Web landing page
WWF pilot	• Built on the Ethereum blockchain • RFID tags and QR codes for tracking • Initiating fish on mobile device • TraSeable traceability platform • IPFS • QR code to access information	• Specific programming knowledge • How to initiate, transfer, and change an asset • Use of digital platform	• WWF • Viant & TraSeable Solutions • Sea Quest Fiji Ltd • Fishermen • Other supply chain actors • Consumer • Certifiers	• Customer app • Management platform • Open registry

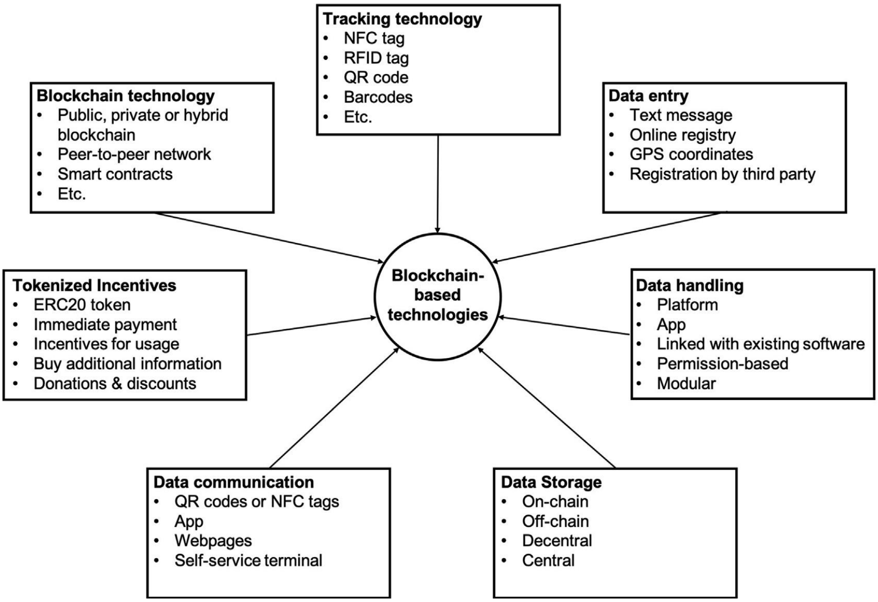


Fig. 2. Overview of technique components.

Strategies to ensure the validity of data entry influence the integrity of the data. For example, in the Provenance case, only previously registered fishermen are allowed to add a new catch avoiding fishermen that have not been screened to enter the system. Other strategies involve setting maximum amounts of an asset that can be registered by one farmer so that the farmer can only register the harvest that can realistically be grown on his plot. These kinds of precautions make fraud and mistakes in entering data more difficult and ensure that the data entered is of high quality.

Interacting with the blockchain generally works through a platform. In the WWF case, the TraSeable traceability platform is used to input data, manage landed catches, or track sales and distribution. The platform can be accessed both via a mobile app and a computer software (Cook, 2018). Provenance allows their platform to be linked with existing Enterprise Resource Planning systems and Point of Sale systems by a common backend. They create a common interface (Provenance, 2016). The IBM Food Trust is built on a permission-based platform, that limits access to data so that businesses always remain in control of commercially sensitive data (IBM, 2019). The platform can quickly locate products and is designed to automate the integration of legacy systems and network data. It is further built as a modular architecture, where customers can choose which components they want to use (IBM Food Trust, 2019a). This platform design is where the core value for actors in the supply chain is created. Depending on its setup actors can access information about every product within seconds.

Data storage can be an issue with blockchain-based technologies, both in terms of speed and costs. Therefore, many traceability projects use an external database to store the data and only put the hash of the data on the actual blockchain. In this way, the information can be secured and verified by the blockchain, while the amount of data on the blockchain is kept small. The WWF case study uses the Inter Planetary File System, a decentralized database, for storing files (Cook, 2018). TE-Food and FairChain also store data off-chain (FairChain Foundation, 2019a; TE-Food, 2017). The setup of the data storage influences the privacy of the data as the information stored off-chain might not be as easy to access. Furthermore, is the amount of data that needs to be conveyed on-chain smaller, which has a positive impact on the speed and the costs of the blockchain-based technologies.

Data communication refers to how blockchain-based technologies share the traceability information with end-consumers. In most cases, a QR code or NFC tag can be scanned in order to access information about the respective product (Cook, 2018; OpenSC, 2019b; Provenance, 2016). In some cases, a mobile app is required for this (TE-Food, 2017). TE-Food additionally offers self-service terminals in supermarkets, where consumers without a smartphone can access the information (TE-Food, 2017). This is where the value for the end-consumer is created. They finally have access to the information of their specific product that has been collected throughout the product's journey.

There are only two out of the six case studies that make use of tokenized incentives. FairChain has experimented with different ways to implement financial tokens. For example, their chocolate brand *The Other Bar* includes a QR code to a 0.25€ token on every bar. This token can either be donated towards planting a new cocoa tree or be used to receive a discount on the next purchase (FairChain Foundation, 2019a). TE-Food uses its token to reward consumers for scanning TE-Food products and using the app. Then they can use the token to pay for additional food quality insights or analysis services (TE-Food, 2017). Including such tokenized incentives into the system design can address different problems and thus, broaden the scope of blockchain-based technology projects in the food supply chain. Tokens bear the potential to additionally implement for example tip-the-farmer or microloan schemes, thus addressing financial inclusion issues.

3.2. Knowledge component

In order to implement blockchain-based technologies in the food supply chain specific knowledge is required for software developers, actors in the supply chain, and other stakeholders.

Software developers need to know programming languages including new ones such as Solidity for Ethereum. Furthermore, they need to possess knowledge of blockchain architecture, off-chain storage options, cryptography, smart contracts, and integration of IoT devices to just name a few. Since the blockchain space is quickly changing, these actors need to follow closely new developments and assess if new components should be tested and implemented as well. They also need to communicate to others what the advantages of their specific implementation is. In the OpenSC case, data science and marine ecology knowledge was further required to set up a machine learning algorithm that verified that the vessel had caught their fish in legal zones (OpenSC, 2019b).

Actors in the supply chain have to be able to use the platform, register a harvest or catch, transfer asset ownership, update assets, and link their existing software to the blockchain-based technology when possible. Usability of the platform can be a key success factor of implementing blockchain-based technologies in the food supply chain. Only when it is easy to use the platform all kinds of users can take full advantage of what the platform offers. Registration of new assets is done differently for different cases. In all cases, the fishermen or farmers need to know which information to include in the initial registration. The farmers in the FairChain case further need to understand in detail their digital wallet and how the token system works (FairChain Foundation, 2019a) in order to use the blockchain-based technology. To ensure such detailed knowledge, TE-Food has developed a guidebook and trainings for local representatives. The local representatives learn among other things how to communicate advantages of using blockchain, how to analyze supply chain processes, how to realize pilot projects, and how to conduct trainings with stakeholders. Additionally, TE-Food has trained over 10,000 farmers, vets, and official users (TE-Food, 2019; TE-Food, 2017). In the FairChain case, it took almost three years for the blockchain to run smoothly. Only then did all actors enter, update, and transfer assessts without problems (FairChain Foundation, 2019a). This shows how important the knowledge component is when implementing blockchain-based technologies in the food supply chain.

It is further necessary that interested parties in the public know how to access raw blockchain data. If no one knows how to access this data, it cannot be checked against the information provided for consumers. Blockchain-based technologies can collect large amounts of data that can in principle be used for data analysis and independent audits. This can ideally help to identify patterns and highlight honest mistakes as well as intentional errors.

3.3. Organization component

As in a typical supply chain, the involved actors include suppliers, processors, distributers, retailers, and consumers. In this study, suppliers are either fishermen or farmers. Other parties involved are software developers and project coordinators. In some cases, software developers and project coordinators can be the same organization like in the Provenance and OpenSC cases (OpenSC, 2019b; Provenance, 2016). In other cases, like the WWF case, several different organizations take up these roles. WWF has the role of a project coordinator, and two external software development companies, Viant and TraSeable Solutions, worked on the software solution (Cook, 2018).

Additionally, auditors can be involved. In the OpenSC case, Ernst and Young audits the data regularly and provides publicly available reports (OpenSC, 2019b). Other partners, such as local NGOs or universities can be involved as well. In the Provenance case, local NGOs register fishermen. The NGO verifies that the fishers follow the guidelines of FairTrade USA, that they are Line Foundation Association Members, and their GPS data when they are on the ocean (Provenance, 2016). FairChain works with both Wageningen and Jimma University (FairChain Foundation, 2019b). Several of the cases further collaborate with certification schemes including FairTrade and MSC (Cook, 2018; OpenSC, 2019a; Provenance, 2016). The fisheries company in the OpenSC case buys carbon offsets under the Australian Government's Carbon Neutral Program that plants trees on their behalf (OpenSC, 2019a). Other important actors are government authorities that may be involved in the process of implementing blockchain-based technologies. Finally, the public is a stakeholder as well. As described above, the public needs to be able to view the raw blockchain data for public blockchains, in order for it to be transparent.

An overview of the typical stakeholders involved implementing blockchain-based technologies in the food supply chain are shown in Fig. 3. The light grey circle shows the stakeholder's role. The outer semi-circle indicates changes on the blockchain. Arrows show the transfer of assets among actors in the supply chain. Thus, implementing blockchain-based technologies in the food supply chain requires substantial and complex iteration of several stakeholders.

3.4. Product component

The final product is a result of what has been described in sections 3.1 through 3.3. The product component can be divided into three elements: consumer, company, and public.

The product (or service) for the consumers is product-specific traceability and information, which can be accessed by scanning a code. In some cases, additional means to access the information are available. OpenSC states they include interactive installations, information for restaurant staff to provide to the guests, as well as websites (OpenSC, 2019a). TE-Food also provides self-service terminals to help consumers without a smartphone reading the QR codes (TE-Food, 2017). Most of the cases provide information about the origin of the product (OpenSC, 2019b; Provenance, 2016). Some of them even include who has harvested the product (FairChain Foundation, 2019b). It is further quite common to communicate compliance with typical labels such as FairTrade or MSC. However, given the level of maturity of these cases under analysis, and the fact that the companies in this study are still testing out different solutions, little detail is currently known about which information is and will be provided to end-consumers in the future. The assessment here is the best possible given the data available.

The product for the companies is the information provided on the management dashboard of their blockchain-based software solution. It can allow the companies to access product information near real-time. A difference between public and private blockchains can be found here as well. In the Provenance and WWF cases, an open registry is available, where anyone can check the raw content of the digital assets (Cook, 2018; Provenance, 2016). The FairChain registry provides access to data to all stakeholders across the entire supply chain removing data asynchrony (FairChain Foundation, 2019c). In the case of IBM Food Trust, on the other hand, only those users with the needed rights can access the data through a platform (IBM Food Trust, 2019b). Raw blockchain data might not be accessible publicly when private blockchains are used such as in the IBM Food Trust case. The availability of data to companies can then facilitate optimization of existing processes. The IBM Food Trust system is module-based and therefore, depending on what a company wants to achieve, it can choose between different

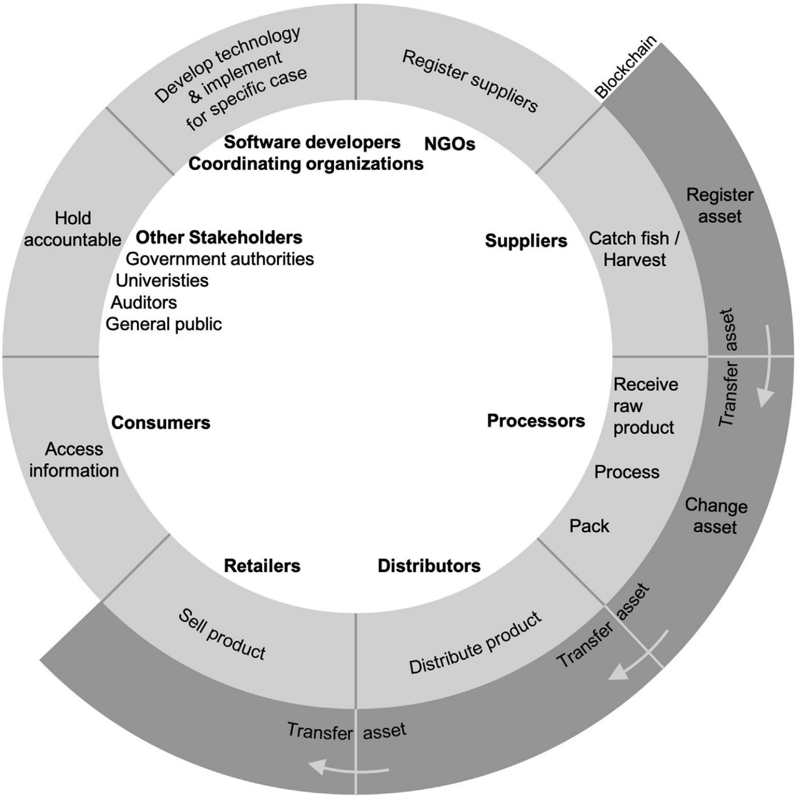


Fig. 3. Stakeholders in a food supply chain implementing blockchain-based technologies, and their roles.

modules such as the module *certifications*, which allows instant access to digitized records (IBM Food Trust, 2019a). In all configurations, the IBM Food Trust focusses on privacy between the different actors. The TE-Food case is also role-based meaning different user roles have differing access and privileges. TE-Food includes information regarding logistics transactions, food safety, an identification management tool, and authority tools (TE-Food, 2017).

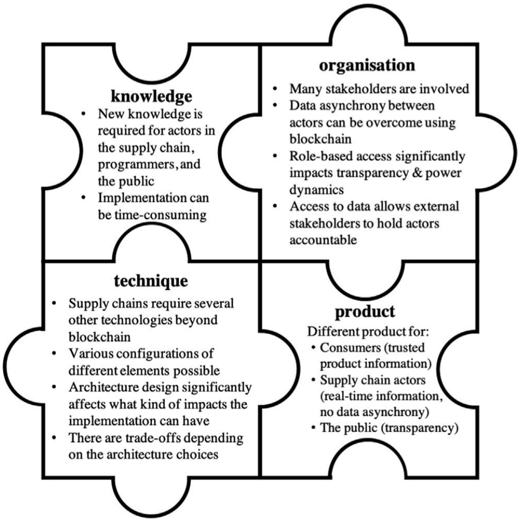
Using public blockchains allow the general public to gain access to information about specific supply chains. This is a higher level of transparency. The data could further be used for independent analyses and audits.

Table 2 provides a synthesis of the findings and Fig. 4 provides an overview of the main findings for each component of the technology assessment.

4. Discussion

4.1. Advantages and drawbacks of blockchain-based technologies in food supply chains

Introducing blockchain-based technologies in the food supply chain leads to a number of trade-offs. Main advantages of introducing such a system include increased transparency, traceability, authenticity, and trust. Blockchain-based technologies allow for verifiable information that are accessible by various actors, who



knowledge
- New knowledge is required for actors in the supply chain, programmers, and the public
- Implementation can be time-consuming

organisation
- Many stakeholders are involved
- Data asynchrony between actors can be overcome using blockchain
- Role-based access significantly impacts transparency & power dynamics
- Access to data allows external stakeholders to hold actors accountable

technique
- Supply chains require several other technologies beyond blockchain
- Various configurations of different elements possible
- Architecture design significantly affects what kind of impacts the implementation can have
- There are trade-offs depending on the architecture choices

product

Different product for:
- Consumers (trusted product information)
- Supply chain actors (real-time information, no data asynchrony)
- The public (transparency)

Fig. 4. Overview of the main findings of the technology assessment.

gain an overview of their supply chains, which is in many cases not possible today. This consequently increases the trust in different actors along the supply chain, enhances a firm's reputation, and can empower consumers. This may allow establishing a direct relationship between different actors in the supply chain. For example, can it be possible for consumers to directly communicate with producer or financially support them through tips or microloans. In some ways, blockchain-based technologies allow long food supply chains to resemble short food supply chains since direct relationships between different actors in the supply chain are possible and the need for many intermediaries may decline. Blockchain-based technologies can also bring trust to existing short food supply chains. Furthermore, the availability of product specific information can allow customers to make informed purchasing decisions. Another main advantage is improved information management. Blockchain-based technologies require the digitization of processes, which allows a company to identify and optimize supply chain efficiencies. Additionally, increased digitization can help to reduce food waste as better information about a product's freshness is available. This information further helps to better control food-borne contaminations. Since information on the blockchain is virtually immutable as it cannot be retrospectively changed, it can reduce the likelihood of fraud and corruption. Another advantage is that blockchain-based technologies can help track sustainability certificates while at the same time reducing auditing due to improved accessibility and quality of information.

Besides these advantages, various drawbacks exist. One major drawback is that the whole process of introducing such blockchain-based technologies in the supply chain requires the participation of many if not all actors along the supply chain, as well as intense coordination and collaboration among them. FairChain made the experience that even if all actors are willing to participate in implementing blockchain-based technologies in the supply chain, it might take some time until all actors initiate, transfer, and change assets correctly and the blockchain is running smoothly. Aside from that, blockchain is a fairly new technology that is not yet mature and insufficiently tested. This means that current projects are testing out new ideas and will evolve further. It also means that some issues such as fragmentation and scalability have not yet been fully solved and that other unexpected problems might occur in the future. While scalability is mainly a problem with public blockchains as only few transactions per second can be processed. For example, approximately 20 transaction per second can be processed on Ethereum (Chauhan et al., 2018), fragmentation occurs when many different private enterprise blockchains are developed independently from each other and are not interoperable. Another issue is that while the data on the blockchain cannot be changed after being entered, the data that is entered can still be of poor quality. Moreover, blockchain-based technologies might be redundant altogether. When one actor owns most of the data along the supply chain the information stored on a blockchain is not really decentralized and a simple centralized server would serve most of the blockchain-based technologies' purpose.

4.2. Blockchain-based technologies from a systemic perspective

This study investigated how blockchain-based technologies in the food supply chain can look like from a systemic point of view. Each case was decomposed into four components highlighting the systemic nature of blockchain-based technologies. It is clear that blockchain-based technologies in supply chains vary in their system architecture. While in all cases consumers access product data by scanning a code and many projects opt for off-chain data storage, the six cases show different system architectures ranging from the choice of public, private or hybrid blockchains to how an asset is registered and to including tokenized incentives. Thus, it cannot be assumed that a generic architecture of blockchain-based technologies in the supply chain exists or would lead to the same impacts as each case suggests different impacts. The examples also show that blockchain is not a panacea. Without the use of other technologies ranging from mobile phones, to tracking technology, and apps a blockchain would be an empty ledger. The combination of certain technologies like e.g. the use of IoT devices to initiate smart contracts can further strengthen the features of blockchains.

4.3. Hypothesis on the role of blockchain to bring positive impact

Based on the analysis of the cases, it is hypothesized that only specific impacts can be attributed directly to the blockchain element of blockchain-based technologies in the food supply chain, whereas other impacts are achieved indirectly by the interaction with other elements in the system of technologies. The difference in system architecture among the six cases makes it complicated to determine what the impact of the blockchain element taken alone is. It is therefore useful to distinguish between direct and indirect impacts. Direct impacts relate to impacts that directly derive from the blockchain element in blockchain-based technologies. Indirect impacts are those generated by blockchain-based technologies but cannot be attributed to the blockchain element alone.

The main direct impact of the blockchain element is to increases trust. A centralized system could deliver a very similar product than a blockchain-based one and it would face fewer bottlenecks when it comes to transaction speed and volume. However, in a centralized system only one version of the data exists: this poses risks of manipulations and requires the users to trust those who have access to the data. Instead, in blockchain-based technologies the entered data is both permanent and virtually impossible to alter due to the decentralized and append-only setup. Further direct impacts include transparency, traceability, and authenticity. Other possible direct impacts are related to using blockchain-based technologies to implement financial services such as for immediate and cross-country payments as in the case of FairChain.

Indirect impacts such as improved data management and supply chain efficiencies are mainly due to the digitization of currently non-digital processes. These are not directly impacted by blockchain itself as they can also be obtained by using centralized, non-blockchain-based technologies. However, implementing blockchain-based technologies may be a strong driver to tackle digitization of supply chain processes, especially where trust is low among supply chain actors. For other indirect impacts, such as increased sustainability or reduced corruption, no strong evidence exists yet. Indirect impacts generally dependent on factors such as: the architecture of the blockchain-based technologies; the blockchain being private, public, or hybrid; if assets are registered in a way that ensures high quality of data; and what information is tracked and how is it displayed for both actors along the supply chain and end-consumers. The system architecture of blockchain-based technologies can be designed to benefit specific actors. It can support the reduction of human rights abuses for farmers or fishermen as well as grant them access to specific markets. Similarly, it can allow companies to collect data of consumer interests and behavior through the use of apps. Thus, the indirect impacts depend as well on the target actor.

4.4. Comparison with previous studies, limitations, and validity

In this study, a focus was put on blockchain-based technologies in the food supply chain by analyzing different cases and looking at their different technology components. While other studies examine blockchain's hypothetical potential in the food supply chain (Galvez et al., 2018; Zhao et al., 2019), this study analyzes six concrete cases. Kamilaris et al. (2019) present ongoing projects of blockchain-based technologies in agriculture and the food supply chain as well, but due to lack of information only look at core descriptive information such as which blockchain has been used and which stage the projects are in (Kamilaris et al., 2019). This analysis of six specific cases permits not only a more detailed assessment, but also a clear decomposition of elements of blockchain-based technologies by taking a systemic perspective. In contrast to previous studies (Chang et al., 2019b; Helo and Hao, 2019), the present analysis did not focus on the *technique* component only, but assessed other components of blockchain-based technologies such as *organization*. This study confirms previous findings that trust, transparency, and authenticity belong to the main advantages of blockchain-based technologies in the food supply chain (Galvez et al., 2018; Kamilaris et al., 2019; Zhao et al., 2019). Kewell et al. (2017) also confirms the importance of the design of blockchain-based technologies in order to achieve specific sustainability objectives.

The findings of this study are heavily based on the information provided by the companies. In order to test the construct validity of our independent analysis, relevant representatives (e.g. the CEO) at each company were approached to critically discuss our findings *a posteriori*, and three out of the six companies engaged in such a discussion. In these cases, it was possible to verify that the initial information retrieved and the understanding of the cases were actual and correct. Only in the FairChain case new information appeared, which is due to a recent change in technology providers. Based on this positive result, for the remaining three cases, where no feedback from the company was given, the information found online as well as the understanding of them was assumed to be correct, although this cannot be ensured with full certainty. Regarding the assessment of internal validity, the results of the within-case analysis are summarized in Section 3 and Table 2 provides an overview of the cross-case pattern matching. A case study database structured according to the technology assessment framework of Müller (2011) was built to increase the reliability of the findings and provide an overview of all cases (cf. Appendix A).

The limitations related to the choice of the six cases deserve to be discussed. The selection of cases can be a challenge and may be influenced by pragmatic reasons such as information availability (Seawright and Gerring, 2008). Thus, other relevant cases may have been neglected. Since a different choice of cases may have led to different findings, the analysis of the six cases was not expected to reflect every possible way of implementing blockchain-based technologies in the food supply chain. For example, another option of tracking technology is using an edible chemical signature for the prevention of product counterfeiting (Leng et al., 2019) or a holistic optimization model could be added as bi-level intelligence for smart production (Leng et al., 2020). Similarly, other stakeholders, technologies, or the like could have been identified by using a different selection of cases. Additionally, not all cases match all criteria equally well. Some are weaker regarding one criterion and stronger regarding another. For instant, the state of implementation of OpenSC is not entirely clear, while the case is strong regarding all other criteria. The IBM Food Trust case, on the other hand, is weaker with respect to the sustainability criteria, but has been implemented to rather mature stage. Nevertheless, the selected cases represent a wide range of blockchain-based technologies within the food supply chain and this selection ensures a solid coverage of this domain. The findings of this study may further hold some validity beyond application in the food supply chain. For example, decentralized off-chain data storage is also used in the healthcare industry to store patient data preserving data privacy and easy access for authorized entities (Kumar et al., 2020).

5. Conclusions

In this study, six cases of blockchain-based technologies in the food supply chain were analyzed using a technology assessment framework. In the assessment, blockchain implemented in the food supply chain was evaluated as an element in a system of technologies looking at four different components: *technique, knowledge, organization,* and *product*. The findings were used to provide a deeper understanding of the state-of-the-art role of blockchain-based technologies in food supply chains. The study returns a sobering picture of what the state-of-the-art of blockchain-based technologies in food supply chains is, and contributes to build a foundation for further analysis and discussion of the social and environmental implications of these technologies.

Blockchain-based technologies find diverse applications in food supply chains due to their immutability and their decentralization of information that increase transparency, traceability and trust. Applied in food supply chains, blockchain is not a stand-alone-technology, but rather part of a system of technologies. Blockchain-based technologies are expected to have a variety of impacts. However, only some (trust, traceability, transparency, authenticity) are directly attributable to the use of blockchain. Other impacts such as improved data management are a side-effect of digitizing non-digital processes for the implementation of blockchain-based technologies in the supply chain. Still other impacts, such as increased sustainability, are expected to be indirectly induced by the use of blockchain-based technologies, but only time will show if this expectation can be fulfilled, especially considering that blockchain itself is still a young technology.

Further research is needed to investigate long-term impacts and confirm whether blockchain-based technologies in the food supply chain will bring the positive change expected. The main challenge to this is the fact that cases are scarce and recent, and the direct and indirect social and environmental improvements related to the technologies have not been systematically monitored or quantified yet. Thus, follow-up studies with blockchain-based technologies in the food supply chain that have been implemented for a longer period of time could be very beneficial in order to close this gap. Furthermore, it would be valuable to assess how the impacts differ in different kinds of supply chains such as long and short ones.

CRediT authorship contribution statement

Susanne Köhler: Conceptualization, Investigation, Data curation, Writing - original draft, Visualization. **Massimo Pizzol:** Conceptualization, Methodology, Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.122193.

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Non-linearity in the Life Cycle Assessment of Scalable and Emerging Technologies

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Given a fixed product system model, with the current computational framework of Life Cycle Assessment (LCA) the potential environmental impacts associated to demanding one thousand units of a product will be one thousand times larger than what results from demanding 1 unit only – a linear relationship. However, due to economies of scale, industrial synergies, efficiency gains, and system design, activities at different scales will perform differently in terms of life cycle impact – in a non-linear way. This study addresses the issue of using the linear framework of LCA to study scalable and emerging technologies, by looking at different examples where technology scale up reflects non-linearly on the impact of a product. First, a computer simulation applied to an entire database is used to quantitatively estimate the effect of assuming activities in a product system are subject to improvements in efficiency. This provides a theoretical but indicative idea of how much uncertainty can be introduced by non-linear relationships between input values and results at the database level. Then the non-linear relations between the environmental burden per tkm of transport on one end, and the cargo mass and range autonomy on the other end is highlighted using a parametrized LCA model for heavy goods vehicles combined with learning scenarios that reflect different load factors and improvement in battery technology. Finally, a last example explores the case of activities related to the mining of the cryptocurrency Bitcoin, an emerging technology, and how the impact of scaling the Bitcoin mining production is affected non-linearly by factors such as increase in mining efficiency and geographical distribution of miners. The paper concludes by discussing the relation between non-linearity and uncertainty and by providing recommendations for accounting for non-linearity in prospective LCA studies.

Keywords: uncertainty analysis, technological learning, efficiency, bitcoin, transportation

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INTRODUCTION

The matrix-based computational structure of Life Cycle Assessment (LCA) is well-described in literature (Heijungs and Suh, 2002) and this framework is often presented as linear, even though the term linear can be interpreted in several ways (Heijungs, 2020). One interpretation is that, mathematically, product systems scale up linearly. This interpretation is based on the fact that, given a fixed product system model, the potential environmental impacts associated to demanding one thousand units of a product are one thousand times larger than results from demanding 1 unit only. The key assumption in such a linear LCA framework is that each activity in the product system will maintain a constant ratio between inputs and outputs, no matter how much product is demanded.

Yet real-world systems are more complex than this and do not follow such a linear trend. Due to economies of scale, industrial synergies, efficiency gains, and system design, activities at different scales and technological maturity will perform differently and display different output to input ratios (Caduff et al., 2011). Their life cycle impact will also be different (Caduff et al., 2012, 2014).

In these cases, the impact *per unit* of product output will be different between a small-scale system, technology, or facility S and a larger one S' that is upscaled and can potentially produce a quantity of product that is – for example – thousands of times higher. While the functional unit of the LCA remains the same, as it is always the impact per 1 unit of product that is calculated, the system used to determine the impact associated with this functional unit is different. Mathematically, the LCA matrix algebra remains unchanged, and even in the new upscaled system, S', calculating the impact of 1,000 units will return a result that is 1,000 times higher than the impact of producing 1 unit. However, the impact of 1 unit produced with this upscaled system S' is not necessarily the same as the impact of producing 1 unit with the original small scale system S. Thus, while non-linearity with respect to the production output is an intrinsic property of the system under analysis, linearity with respect to the functional unit is an intrinsic property of the LCA model used to study this system. This is precisely the mismatch that the present study intends to address.

This mismatch between model and reality becomes critical and potentially problematic in the study of technology upscaling, and particularly in the case of emerging technologies. For example, upscaling effects for green technologies are substantial and well-documented (Grubb, 2004; Piccinno et al., 2016; Nemet et al., 2018) and can lead to increases in efficiency and reduction in the impact per output ratio for a specific activity. It is notably the case with renewable energy systems, where the initial environmental burden of manufacture spreads as the load factor of the plant increases (Padey et al., 2013; Miotti et al., 2017).

This effect is then particularly evident for emerging technologies in which data are available only on a pilot scale, and it is realistic to expect substantial improvements when reaching industrial scale. With emerging technologies, a massive increase in production volumes lead to reduction in the environmental burden thanks to economies of scale and technological learning (Piccinno et al., 2016; Sacchi et al., 2019). Miotti et al. (2017) illustrated such a case, where the environmental impact of hydrogen fuel cell stacks is reduced by two thirds as the production volume increases from 200 units/year in 2014 to 500,000 units in 2030.

It is worth noting that the upscaling challenge and potential gain is highly technology-specific. For example, the upscaling of emerging technologies for the treatment of biomass are challenged by the need to work continually and keep controlled physical-chemical conditions but can benefit from synergies such as for example heat recovery aspects that are not appreciable at pilot scale. Another example is the mass-production of complex new technologies such as fuel cells that depend heavily on automatization and robotics and are substantially different from the manual work of manufacturing these technologies in small quantities.

Thus, modeling the upscaling of emerging technologies goes beyond the sole use of upscaling relationships. In their recent review Tsoy et al. (2020) list several data estimation methods relevant in this context such as process simulation, manual calculations, molecular structure models (only for chemical technologies), and use of proxies. According to these authors, a framework to create LCAs of new technologies at scale includes collaborating with technology experts to define hypothetical upscaled scenarios. This mirrors previous findings of Arvidsson et al. (2017) who also recommend modeling various scenarios using literature, expert interviews, simulation software, and a combination of these methods.

While current research on the LCA of emerging technologies (Valsasina et al., 2017; Bergerson et al., 2019; Blanco et al., 2020) deals indirectly with non-linear effects, the non-linear relations between technological upscaling and life cycle assessment has not been explicitly covered in the literature.

As already pointed out by Heijungs (2020) the impact of a product system on a small interval looks like a straight line, but on a larger interval it becomes non-linear. What remains unaddressed is on a practical level why, where, and how much this is a problem.

In this context, the main objective of this article is to present and discuss different cases of LCAs of product systems that do not scale up linearly. The study intends to show the diversity of potentially non-linear cases to derive more general considerations on how extensively non-linearity can become a problem in the LCA of scalable and emerging technologies as well as to propose possible ways to address this problem.

METHODS

This work is based on the analysis of different case studies. The cases are illustrative and were selected because they allow the problem of non-linearity in scalable and emerging technologies to be addressed specifically. The cases were also chosen in order to cover different levels of complexity and various types of uncertainty. Finally, the cases were chosen pragmatically based on data directly available from previous and current research work of the authors on scalable and emerging technologies. All cases were analyzed using the ecoinvent database (Wernet et al., 2016) with different versions and system models depending on the case, cf. **Supplementary Table 3**. The impact of the different systems under analysis was characterized using the midpoint impact indicator Global Warming measured in kg of Carbon Dioxide equivalents (kg CO_2-eq) using the IPCC 2013 method with a time horizon of 100 years (IPCC, 2013). The analysis was performed using the open source software Brightway2 (Mutel, 2017) unless specifically indicated. Code and data used for the analysis can be openly accessed at an online repository (Pizzol et al., 2020).

Estimating the Effect of Improvements in Technology Efficiency at Database Scale

The first case explores how efficiency gains that are theoretically achievable via technology upscaling result in changes in impacts, by taking a whole life cycle inventory database as unit of analysis. The hypothesis is that data used to build a database bottom-up via industry surveys — like in the case of ecoinvent (Wernet et al., 2016)— may not always reflect technologies at their highest readiness level or technological maturity. In other words, the datasets representing some activities might have been collected from a plant or facility that does not operate at large industrial scale and is therefore far from achieving its potential maximum efficiency. The data supplier might thus have measured an exchange in a process that is far from maximum efficiency.

The challenge in studying the effect of this inaccuracy at database scale is then two-fold. On one hand, it is virtually impossible to know in detail which flows can be improved and where the upscaling uncertainty lies. It then becomes necessary to assume an upscaling uncertainty for each exchange in each activity, intended as a probability of being wrong about the efficiency of this activity regarding the input exchange. On the other hand, it is reasonable to expect that the effect of improving the efficiency of one or more activities in the database would be rather different depending on the activity that is considered for the analysis, meaning the functional unit for which the life cycle impacts are calculated.

To tackle these challenges, a computer simulation was performed where the change in the environmental burden of a sample of activities from the ecoinvent database was measured after increasing the efficiency of a number of other activities, thus simulating an improvement that is potentially achievable via technology upscaling or learning effects. Mathematically, the efficiency improvement in an activity is here achieved via a reduction c in the amount of technosphere or biosphere input x required to obtain the production output y.

$$y = f\left(x\right) = cx \quad with\; 0 < c < 1 \tag{1}$$

The idea was then to simulate this efficiency improvement as realistically as possible at whole database scale to provide a theoretical but indicative idea of how much uncertainty may be introduced by non-linearities associated with technology upscaling.

The ratio r was calculated by defining h as the impact vector, $\mathbf{Q}$ as the characterization matrix, $\mathbf{B}$ as the intervention matrix, $\mathbf{A}$ as the technology matrix, and f as the demand vector (Heijungs and Suh, 2002).

$$r = \frac{h'}{h} \tag{2}$$

Where h was taken as the "base" value of the impact of an activity before changing its efficiency.

$$h = \mathbf{Q}\boldsymbol{B}(\boldsymbol{y})\left(\boldsymbol{A}(\boldsymbol{y})\right)^{-\boldsymbol{1}}\boldsymbol{f} \tag{3}$$

And h' was obtained by improving the efficiency of specific activities in the database. This is further explained in the following, by using different examples of increasing complexity.

The first simple example measured the effects of progressively increasing the efficiency of coal power plants in the production of electricity. This example allowed working under rather controlled conditions before dealing with the intrinsically high variability of the entire database, due to the fact that the database includes several types of activities.

Initially, the improvement was only modeled in terms of a reduction in energy and material inputs. This means that only the values in the technosphere matrix were changed to obtain a new technosphere matrix $\mathbf{A}'$ and calculate h':

$$h' = \mathbf{QB}\boldsymbol{A}'^{-\boldsymbol{1}}\boldsymbol{f} \tag{4}$$

Where the $a'_{i,j}$element of $\mathbf{A}'$ was obtained as:

$$a'_{i,j} = \; ca_{i,j} \qquad where\; i \neq j \tag{4.1}$$

Where a_j is any matrix column representing coal-based electricity production, and all coal-based electricity production activities in the database were simultaneously modified. c is the fixed coefficient of efficiency improvement. Note that $\mathbf{A}$ is assumed square with diagonal values equal to 1. A more visual example is provided below considering the technology matrix $\mathbf{A}$ where each unit process j has production output $q_j$and technosphere inputs $x_{i,j}$ and where both columns $a_{j=1}$ and $a_{j=2}$ represent coal power plants:

$$\mathbf{A} = \begin{pmatrix} \frac{q_1}{q_1} = 1 & -\frac{x_{1,2}}{q_2} = a_{1,2} & \ldots \\ -\frac{x_{2,1}}{q_1} = a_{2,1} & \frac{q_2}{q_2} = 1 & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} = \begin{pmatrix} 1 & a_{1,2} & \ldots \\ a_{2,1} & 1 & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} \tag{4.2}$$

$\mathbf{A}'$ is obtained by multiplying the off-diagonal values of column $a_{j=1}$ and $a_{j=2}$ by the same coefficient of efficiency improvement. In this upscaled system the production output is denoted $q'_j$and technosphere inputs are denoted $x'_{i,j}$. The assumption is then that $x'_{i,j}$ is not just proportional but more efficient than proportional:

$$x'_{i,j} = \; ca_{i,j}q'_j \tag{4.3}$$

This allows to obtain:

$$\mathbf{A}' = \begin{pmatrix} \frac{q'_1}{q'_1} = 1 & -\frac{x'_{1,2}}{q'_2} = ca_{1,2} & \ldots \\ -\frac{x'_{2,1}}{q'_1} = ca_{2,1} & \frac{q'_2}{q'_2} = 1 & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} = \begin{pmatrix} 1 & ca_{1,2} & \ldots \\ ca_{2,1} & 1 & \ldots \\ \ldots & \ldots & \ldots \end{pmatrix} \tag{4.4}$$

This simple example was then extended to additionally consider the improvement in terms of emission reduction together with the reduction in material and energy requirements. This means that h' values were this time obtained by changing both the values in the technosphere matrix and the values in the intervention matrix.

$$h' = \mathbf{QB}'\boldsymbol{A}'^{-\boldsymbol{1}}\boldsymbol{f} \tag{5}$$

Where the $a'_{i,j}$element of $\mathbf{A}'$ is obtained as in Equation (4.1) and the $b'_{i,j}$ element of $\mathbf{B}'$ is obtained as:

$$b'_{i,j} = cb_{i,j} \tag{5.1}$$

Where a_j and $b_j$are the columns representing coal-based power plants in each matrix. More visually, considering the intervention matrix $\mathbf{B}$ where each unit process j has production output $q_j$and environmental exchanges $z_{i,j}$ and where both columns $b_{j=1}$ and $b_{j=2}$ represent coal power plants, then:

$$\boldsymbol{B} = \begin{pmatrix} \frac{z_{1,1}}{q_1} = b_{1,1} & \frac{z_{1,2}}{q_2} = b_{1,2} & \dots \\ \frac{z_{2,1}}{q_1} = b_{2,1} & \frac{z_{2,2}}{q_2} = b_{2,2} & \dots \\ \dots & \dots & \dots \end{pmatrix} = \begin{pmatrix} b_{1,1} & b_{1,2} & \dots \\ b_{2,1} & b_{2,2} & \dots \\ \dots & \dots & \dots \end{pmatrix} \tag{5.2}$$

The improvement is again described as an increase in efficiency:

$$z'_{i,j} = cb_{i,j}q'_j \tag{5.3}$$

To obtain the upscaled intervention matrix $\boldsymbol{B}'$:

$$\boldsymbol{B}' = \begin{pmatrix} \frac{z'_{1,1}}{q'_1} = cb_{1,1} & \frac{z'_{1,2}}{q'_2} = cb_{1,2} & \dots \\ \frac{z'_{2,1}}{q'_1} = cb_{2,1} & \frac{z'_{2,2}}{q'_2} = cb_{2,2} & \dots \\ \dots & \dots & \dots \end{pmatrix} = \begin{pmatrix} cb_{1,1} & cb_{1,2} & \dots \\ cb_{2,1} & cb_{2,2} & \dots \\ \dots & \dots & \dots \end{pmatrix} \tag{5.4}$$

The simulation consisted in calculating r values (Equation 2) using Global Warming impact values obtained via Equations (3–5) for 10 randomly selected activities (10 different f) in the database and nine progressively increasing values of c ranging from 0.2 to 1.0 in 0.1 increments to cover a theoretical efficiency increase up to 400%.

This simple example allowed a clear understanding of the relationship between efficiency increase and impact. It did not, however, allow conclusions to be drawn that were generalizable at a whole database level. Thus, a more complex example was introduced by measuring the effects of more random and widespread improvements in the efficiency of different activities in the database.

The approach presented in Equations (3–4.4) was upscaled to database level by simultaneously modifying all *transformation* activities in the ecoinvent database. In principle, efficiency gains can only be observed in *transformation* activities, as opposed to *market* activities which only represent the combined supply of similar products based on trade statistics. Again, at first only the technosphere exchanges were modified and h' calculated as in Equation (4), but this time $a'_{i,j}$was obtained as:

$$a'_{i,j} = C_k a_{i,j} \quad where\ i \neq j \tag{4.5}$$

Where a_j is any matrix column representing a *transformation* activity, and all *transformation* activities in the database were simultaneously modified. C_k is again a coefficient with value between zero and one ($0 < C_k < 1$) representing efficiency improvements, but as opposed to c that was fixed, C_k was instead randomly sampled from a specific probability distribution.

The following presents a visual example of how the $\mathbf{A}'$ matrix was obtained in this more complex simulation, assuming that columns $a_{j=2}$ and $a_{j=4}$ of $\mathbf{A}$ are both *transformation* activities and $c_1, c_2, c_3, \dots$ are randomly sampled instances of C_k (i.e., randomly sampled coefficients).

$$\boldsymbol{A}' = \begin{pmatrix} 1 & c_1a_{1,2} & \dots & c_4a_{1,4} \\ \dots & 1 & \dots & c_5a_{2,4} \\ \dots & c_2a_{3,2} & 1 & c_6a_{3,4} \\ \dots & c_3a_{4,2} & \dots & 1 \end{pmatrix} \tag{4.6}$$

Once again, this example was further extended to consider both improvements in terms of reduced material and energy requirements and in terms of emission reductions. Thus, $a'_{i,j}$ was obtained as in Equation (4.6) and $b'_{i,j}$ as:

$$b'_{i,j} = C_k b_{i,j} \tag{5.5}$$

This operation was performed on all b_j columns representing *transformation* activities and using randomly generated coefficients as from Equation (5.5). Thus, the way $\boldsymbol{B}'$ was obtained in was similar to Equation (4.6) with the only difference that all values in the columns $b_{j=2}$ and $b_{j=4}$ are multiplied by a coefficient and not only the off-diagonal ones.

$$\boldsymbol{B}' = \begin{pmatrix} \dots & c_1b_{1,2} & \dots & c_5b_{1,4} \\ \dots & c_2b_{2,2} & \dots & c_6b_{2,4} \\ \dots & c_3b_{3,2} & \dots & c_7b_{3,4} \\ \dots & c_4b_{4,2} & \dots & c_8b_{4,4} \end{pmatrix} \tag{5.6}$$

The simulation at entire database level consisted in performing the operations described in Equations (4.5, 5.5) repeatedly 1,000 times, randomly sampling different coefficients at each iteration, and then calculating r values via Equation (2) using Global Warming impact values obtained via Equations (3–5) for 50 randomly selected *market* activities (fifty different f) in the database. In order to provide clearer results, treatment and waste management activities were excluded from the selection as these can return negative results and complicate the interpretation. The result was a matrix of 1,000 × 50 r values where rows represented iterations and columns represented the *market* activities under analysis. Moreover, this simulation was performed in four different scenarios obtained by using two versions of the same database and two probability distributions of C_k to appreciate the differences due to modeling choices and assumptions. In particular, both the consequential and cutoff version of the ecoinvent v.3.6 database were used and both the beta distribution $C_k \sim Beta(\alpha, \beta)$ with $\alpha = 5\ and\ \beta = 1$, and an uniform distribution $C_k \sim U(0, 1)$.

The reason for choosing a beta distribution, which resembles an exponential distribution between zero and one, is that it can be considered a suitable model for the random behavior of percentages and proportions. As the specific exchanges that can potentially be improved are unknown to the authors, it was assumed that most exchanges are already close to maximum efficiency. The Beta distribution with the selected values allows modeling this assumption, i.e., the probability to sampling a value close to 1 is higher than the probability of sampling a value close to 0. Using a beta distribution was a middle ground between using the same efficiency gain for all input exchanges of an activity and completely randomly selecting efficiency from a uniform distribution between zero and one — which was also performed for the sake of comparison.

The reason for performing the simulation on two versions of the ecoinvent database was that the consequential system model adopts system expansion as a method to solve multifunctionality, resulting in a number of activities being associated with a (mathematically speaking) negative impact. This produces r values >1 and can skew the distribution of results to the right. The comparison with the cutoff version allowed appreciating this additional factor of variability.

Non-linearity in Upscaling Services, the Case of Freight Transportation

The first case was theoretical, and only considered potentially achievable changes in the value of specific flows while not explaining how in detail these changes might manifest.

To show more concretely how a specific technology might display a different behavior at different scales a second case was chosen that considers the transportation of goods. Transportation systems are a case where a non-linear behavior in upscaling can be observed. This can be exemplified with freight transportation where fluctuations of the load factor or fluctuations in the vehicle size and carrying capacity can affect the environmental burden per ton transported in a non-linear manner (Rizet et al., 2012; Pizzol, 2019).

This case provides two examples on how technology upscaling and technology improvement affect the environmental performance of transportation via heavy duty trucks in a non-linear manner. The first example of a 40-ton diesel truck was considered to highlight the non-linear relation between the load factor of the system and its environmental performance per tkm of transportation. The second example of a battery electric truck was used to highlight the non-linear relation between the driving range autonomy and its environmental performance per tkm. These models allow accounting for the variability in the operating conditions of two different transportation technologies at different scales.

The parametrized LCA model for heavy goods vehicles *carculator_truck* (Sacchi et al., submitted) was used for this case. The tool models trucks of various powertrain types (i.e., internal combustion engine, battery electric, fuel cell electric) and sizes (i.e., from 3.5 to 60 t of gross weight), across time (i.e., from 2000 to 2050), and for different duty cycles (i.e., urban and regional delivery, long haul). Further information is available from the online documentation of the library[1] including a detailed description of data sources and modeling assumptions. The library uses the cutoff system model of the ecoinvent v.3.7 database to model the supply of material, services, and energy.

The first example, highlighting the effect of technology upscaling, focused on assessing the non-linear relation between the load factor of a truck and its global warming impact per tkm. To do that, a 40-ton articulated curtainside truck with a diesel engine and a lifetime of 1 million km was modeled with a load factor ranging from 0 to 100% with a 1% increment step. For each increment in the load factor, the vehicle components and drivetrain were sized, after which the tank-to-wheel energy consumption of the vehicle was calculated given a specific driving cycle.

In this case, the driving cycle chosen reflects long haul operations. The tank-to-wheel energy consumption entails the energy needed to overcome different types of resistance, such as the inertia of the vehicle itself, the rolling resistance, the aerodynamic drag, the road gradient, as well as resistance in the transmission shaft and the engine. The curb mass m_c [t] of the vehicle was obtained as being the sum of the components' mass, including the energy storage mass m_e, but excluding passengers and cargo (Equation 6). The available payload m_P is the difference between the gross mass m_g of the vehicle and its curb mass (Equation 6.1). When the vehicle is "built," its material and energy inventory is solved. Such inventory contains all the relevant life cycle phases of the vehicle, including its manufacture, maintenance, use and end-of-life. The life cycle Global Warming impact per tkm h_t [kg CO$_2$-eq/tkm] is obtained by dividing the total life cycle carbon emissions of the vehicle h_l [kg CO$_2$-eq] with the number of kilometers driven l [km] and the payload transported, which is itself the product of the available payload m_p and the load factor r [without unit] (Equation 6.2).

$$m_c = m_e + \ldots \tag{6}$$

$$m_p = m_g - m_c \tag{6.1}$$

$$h_t = h_l l^{-1}(m_p r)^{-1} \tag{6.2}$$

A second example, highlighting the effect of technology improvement, focused on assessing the non-linear relation between range autonomy (the distance a truck is required to drive without refueling) and the truck's global warming impact per tkm in 2020 and 2050. The analysis followed a similar approach as in the first simulation but considered a 40-ton articulated truck powered by an electric powertrain instead of a diesel engine. In this case, the energy storage mass m_e was sized based on the required range autonomy a [km], tank-to-wheel energy consumption of the vehicle E_w [kWh/km], the depth of battery discharge b [without unit] and the energy density of the battery cells d [kWh/kg] (Equation 6.3). As the range autonomy increases, the mass of the energy storage increases as well, reducing the maximum payload available by an equivalent amount. This can however be compensated by an increase in the battery cell energy density. It is worth noting that unlike diesel powertrains, a part of the energy used for braking during downhill or decelerating sections of the driving cycle is recovered here using the electric motor. Also, as a new curb mass is defined, the tank-to-wheel energy consumption of the vehicle needs to be re-calculated, which itself redefines a new energy storage mass and curb mass. Such process stops when the curb mass of the vehicle converges.

$$m_e = aE_w b^{-1} d^{-1} \tag{6.3}$$

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[1] https://carculator-truck.readthedocs.io/en/latest/index.html

The energy storage mass was modeled using lithium-ion batteries based on a nickel manganese cobalt chemistry. It assumed a battery cell energy density of approximately 0.2 kWh per kg of cell today, increasing to 0.5 kWh per kg in 2050 (Ding et al., 2019) and a depth of discharge of 20%. Material and energy inventories were solved for a required range autonomy of 100 to 1,200 km, by increment step of 100 km. As with the diesel truck, the resulting carbon emissions were normalized to a tkm by dividing the overall burden successively by the number of kilometers driven along the use phase of the vehicle and the cargo mass transported — see Equation (6.2).

Non-linearity in Upscaling Networks, the Case of Bitcoin Mining

A key feature of the previous cases is that while the performance of the product system is different at different scales due to improvements, the fundamental structure of the system does not change. More concretely, the structure of the inventory model remains the same and only the values of its exchanges change. However, there are situations where the upscaling of a technology might result in a structural change of the product system itself.

To account for this type of change, the third case considers the mining of Bitcoin as emerging technology and explores the non-linear effects of expanding its mining network. This builds on previous research (Köhler and Pizzol, 2019) that considers a model of the network of Bitcoin miners as a snapshot of the year 2018. In rather simplified mathematical terms, in this model the life cycle impact h_m [kg CO_2-eq/TH] associated with mining is given by the product of the horizontal vector s_l [without unit] representing the share of mining performed in each location with the vertical vector h_l [kg CO_2-eq/kWh] representing the life cycle impact of electricity production in each location, and the energy consumption E_m [kWh/TH] of the machines (special computers) used for mining.

$$h_m = s_l h_l E_m \tag{7}$$

In turn, the energy consumption is a function of the hash rate p [TH/s], and the power P [W] of the machine.

$$E_m = P p^{-1} \tag{8}$$

This product system does not scale linearly, which is mainly due to two factors: the new mining equipment employed is more energy efficient than the average equipment for 2018, and new mining capacity is not installed proportionally in current locations and is even installed in new locations.

To address this upscaling issue, previous research (Köhler and Pizzol, 2019) adopted a consequential approach and attempted to provide an outlook of the Bitcoin mining network upscaling for early 2019. Since then, however, the hashrate of the Bitcoin mining network has increased and both mining efficiency and miner locations have continued to change. This study considers new upscaling scenarios for early 2020 that allow a comparison with the upscaling scenarios of early 2019 taken from the previous study. The upscaling scenarios consider changes in location of miners and energy efficiency of the mining equipment.

A baseline business-as-usual (BAU) scenario was first obtained (Equation 7). This BAU scenario illustrated linear growth and was taken as reference against which all other scenarios were compared. The same prospective model for early 2019 as in the previous study (Köhler and Pizzol, 2019) was used in the calculation. The result is the Global Warming impact for increasing computing demand by one tera hash (TH).

Scenario 1 represented instead a location-sensitive scenario where new mining facilities are only installed in more competitive conditions (e.g., lower energy prices). In this scenario, the impact of the upscaled system h'_m was calculated as:

$$h'_m = s'_l h_l E_m \tag{7.1}$$

Scenario 2 represented then an equipment-sensitive scenario, where only more efficient mining equipment was used, intended as equipment that uses less energy in mining ($E' < E$).

$$h'_m = s_l h_l E'_m \tag{7.2}$$

Finally, Scenario 3 assumed both more efficient mining equipment and more competitive mining locations.

$$h_m = s'_l h_l E'_m \tag{7.3}$$

For the BAU scenario and Scenario 2, which were not location-sensitive, the share of mining in each location $s_l$was modeled using the distribution reported in **Table 1**. The data was taken from the Cambridge Bitcoin Electricity Consumption Index for September to December 2019 (Cambridge Centre for Alternative Finance, 2020). Only locations that contributed at least 2% (rounded) were included. The percentages were then scaled to 100%. For the location-sensitive Scenarios 1 and 3, the share of mining in each location s'_l reported in **Table 1** was used. The data shows the difference from miner distribution between Sept-Dec 2019 and January–March 2020s (Cambridge Centre for Alternative Finance, 2020). Those locations where an increase in shares compared to September–December 2019 has occurred were included. Their shares were then scaled to 100% representing the marginal mining locations.

Details on the parameters used to model the material and energy requirements of the mining equipment in the different scenarios are provided in **Table 2**. For the BAU scenario and Scenario 1, data regarding the amount of equipment still in use was taken from "The Bitcoin Mining Network–December 2019 Update" (Gibbons and Bendiksen, 2019). The specifications for each machine were taken from the homepage ASIC Miner Value (ASIC-MinerValue, 2020) and a mining equipment mix for 2019 was modeled from these data sources. For the equipment-sensitive scenarios, the mining equipment that was still profitable and already produced by the beginning of 2020 was identified. A mining equipment mix for Scenario 2 and Scenario 3 was then determined based on the share of equipment in terms of profitability. Additional details on the methodology used to derive the mining equipment mixes are provided in **Supplementary Tables 1**, **2**.

TABLE 1 | Distribution of mining locations s_l and s'_lin different scenarios.

Location	s_l **BAU and Scenario 2 %**	s'_l **Scenario 1 and 3 (Location-sensitive)**
Xinjiang	31.1	67.0%
Sichuan	26.4	–
Yunnan	8.9	–
Nei Mongol	8.7	6.1%
Russia	7.1	–
US	6.2	–
Malaysia	4.2	3.0%
Gansu	3.1	–
Iran	2.3	8.1%
Kazakhstan	2.0	15.8%

TABLE 2 | Parameters used to model the energy consumption E_m and E'_m of the mining equipment in the different scenarios.

Parameter	E_m **BAU and Scenario 1**	E'_m **Scenario 2 and 3 (Equipment-sensitive)**
Hash rate (p)	21.6 TH/s	63.67 TH/s
Power (P)	1660 Watt	2541 Watt

RESULTS

Non-linearities in Efficiency Improvements at Large Scale

Results reported in **Figure 1** show clearly how a progressive increase in efficiency of electricity production in coal-based power plants results in a non-linear decrease in impact for several activities. The effect of such improvement, that one could theoretically ascribe to generic technological learning, is not equally pronounced for all activities under analysis, as this depends on the direct and indirect upstream inputs of electricity produced from coal to these activities. **Supplementary Figure 1** shows the similar effect obtained by performing the analysis on a different database system model.

Results reported in **Figures 2**, **3** show how a random change of efficiencies for several transformation activities is reflected on the impact of several randomly selected database activities. This effect is highly dependent on the activity under analysis, and no clear relationship can be identified between the change in efficiency and its effect. While the effect can be explained for single activities it is not generalizable in a straightforward way at database level, as each activity will behave differently and might be affected substantially even if the change occurs several steps upstream in its life cycle. Boxplots for each of the 50 functional units considered are provided in Supplementary information, **Supplementary Figures 2–5**.

It is important to focus on the comparison between the random uniform sampling and the random beta sampling of efficiency improvements. The interesting aspect is that none of the distributions in fact resembles the distribution of the efficiency improvements. In other words, the distribution of the output does not reflect the distribution of the input, as it would be expected if the effect was linear. This confirms once again that the effect of technology upscaling on the impact of a system is non-linear.

A further note should be added on the comparison between databases and how the high variability in the type and nature of activities considered affects the results. In **Figure 2**, in all distributions and database versions, a small number of invariant activities can be observed (the ratio between base and simulation result close to one). These are activities that are not affected substantially by a change in efficiency for transformation activities; for example, "*market for land tenure, arable land, measured as carbon net primary productivity, perennial crop*" and "*market for electricity, high voltage.*" This might be due to several reasons, for example because they link to transformation activities that do not include any technosphere exchange or that only include biosphere exchanges that do not contribute to the Global Warming impact category. The comparison between **Figures 2**, **3** allows appreciation of this additional variability in the database.

Furthermore, when using the consequential system model of the ecoinvent database, ratios higher than one can be observed. This is explained by the fact that the substitution (system expansion) method is used to solve multifunctionality and therefore a number of activities return a negative impact. For these, an increase in efficiency as modeled in this simulation results in an increase in net impact.

Non-linearities in The Impact of Freight Transportation

As expected, total carbon emissions increase as the utilization rate of the available payload increases. As shown in the left panel of **Figure 4**, this corresponds to the minimum emission over the entire lifetime of the 40-ton diesel vehicle of 1 million kg of CO_2-eq. with a load factor of 0%, to 1.6 million kg of CO_2-eq. for a load factor of 100% (i.e., the transport of 25 t of cargo). On a per tkm basis, the first ton transported has a Global Warming impact of 0.6 kg CO_2-eq., against 0.06 for the 25th ton, as shown in the center panel of the same figure. Hence, the assumed initial load factor is important in determining the environmental burden of a ton transported over 1 km.

Similarly, it appears clear that transporting 1 ton of cargo (which corresponds to a load factor of about 40%) yields a different result than transporting 10 times 1 ton of cargo.

The right panel in **Figure 4** shows the change in carbon emissions on a tkm basis associated with adding an extra ton of cargo, given an initial amount of cargo already loaded. For example, adding 1 ton of cargo with an initial load of 5 tons reduces the impact per tkm by about 0.05 kg CO_2-eq. On the other end, past an initial load of 15 t, the benefits of adding an additional ton on the per tkm impacts become comparatively negligible.

In the second case, where the range autonomy of a 40-ton battery electric truck is incremented by steps of 100 km, another trend is observed. As the range autonomy increases, the available

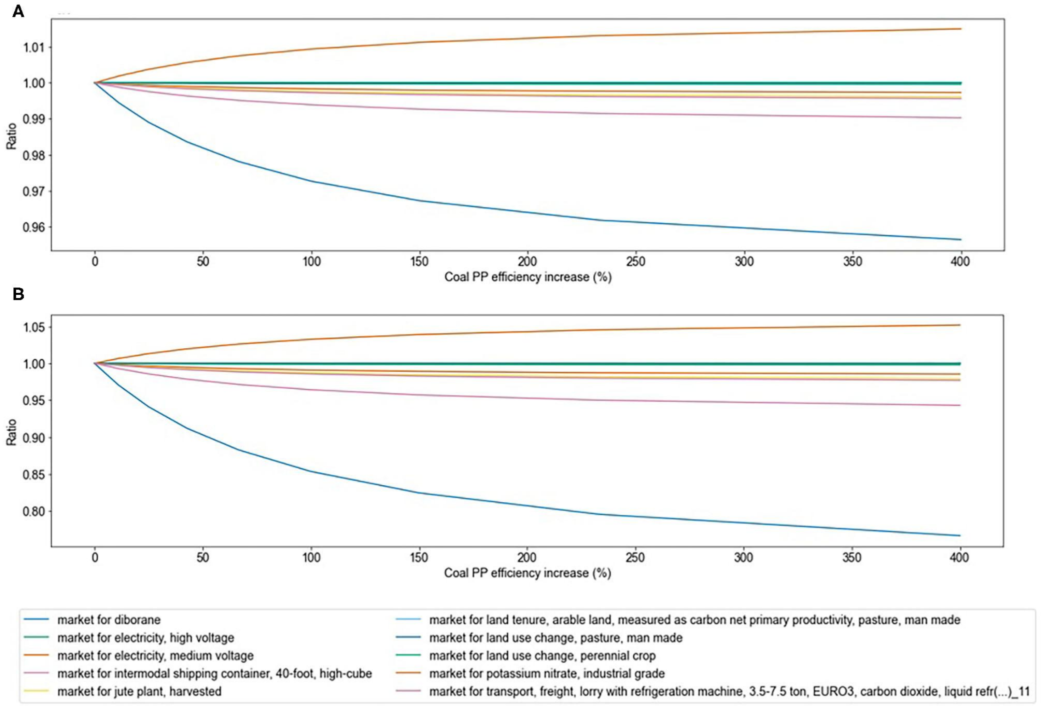

FIGURE 1 | Effect of improving from 0–400% the efficiency of electricity production in all coal-based power plants datasets of the ecoinvent database (consequential) on the Global Warming impact calculated for 10 randomly selected activities from same database. The effect is expressed as the ratio between the impact of the improved dataset and the impact of the unmodified dataset: values closer to 1 indicate a weaker effect. **(A)** shows the effect of improving only technosphere exchanges, while **(B)** the effect of improving both technosphere and biosphere exchanges.

payload decreases because of the mass increase of the energy storage components. This effect is different for the cases of 2020 and 2050, due to improvements in the energy density of battery cells. On the left panel of **Figure 5**, a required range autonomy of 100 km with a truck in 2020 allows to transport 25 t of cargo for 0.95 million kg of CO_2-eq., while a range autonomy of 1,000 km only allows transporting 10 t of cargo for a total emission of 2.2 million kg of CO_2-eq. The dark blue area, which represents kg of CO_2-eq. emissions associated to electricity supply, and indirectly, energy consumption, does not vary much as the range autonomy increases. This is because the driving mass of the vehicle does not increase despite the energy storage becoming voluminous, as the cargo mass diminishes. It also explains why the emissions associated to the road manufacture and maintenance remain constant, as they are scaled on the vehicle mass. This indicates a certain limitation of battery electric trucks for long distance trips.

This pattern is equally illustrated in the central panel of **Figure 5**, where the performance per tkm of both trucks (2020 and 2050) is illustrated. Transporting 1 ton of cargo with a truck designed with a range autonomy of 1,200 km yields a different result per tkm than transporting the same ton of cargo with two trucks consecutively designed to have an autonomy of 600 km each. However, improving the energy density of battery cells by a factor of 2.5 between 2020 and 2050 yields to improvements far superior to a factor of 2.5 as the range autonomy increases. This is explained by the fact that the truck in 2050 would only reduce its payload capacity by 4 t to increase the autonomy range from 100 to 1,200 km, against 19 t for the truck in 2020.

The right panel in **Figure 5** shows the change in carbon emissions per tkm from adding 100 km of range autonomy, function of an initial range autonomy, for both trucks. For example, for a 40-ton battery electric truck in 2020 with an initial range autonomy of 200 km, adding another 100 km of autonomy will only add 0.05 kg CO_2-eq., to a tkm. This is to be contrasted with adding 100 km of range autonomy to the same truck with an initial autonomy of 1,000 km, where such change would add 0.2 kg CO_2-eq. to the impacts per tkm. In parallel, a loss in utility is also observed as adding 100 km of range autonomy would lead to losing 2 t of payload capacity for the truck in 2020 (from 10 to 8 t), against <0.1 t for the truck in 2050. Thanks to expected improvements by 2050, increasing the range autonomy of the vehicle does not lead to marginally increasing emissions,

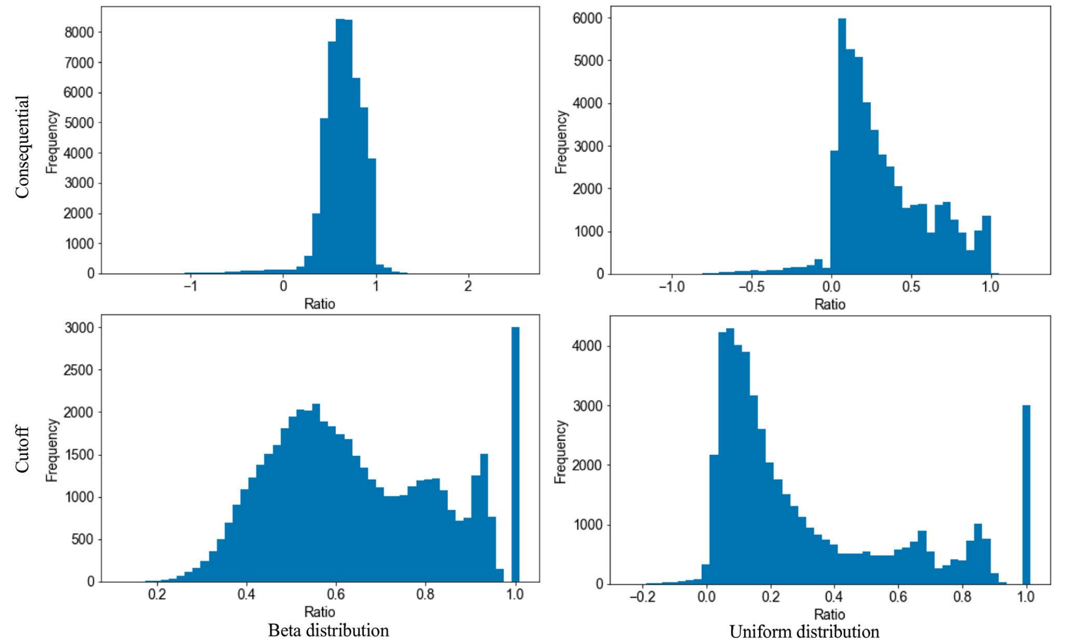

FIGURE 2 | Effect of efficiency improvements at database scale. The effect is obtained by randomly modifying the efficiency of all transformation activity datasets in the ecoinvent database and calculating the global warming impact for 50 randomly selected market activities. The effect is expressed as the ratio between the impact calculated using the improved datasets and the impact calculated using the unmodified dataset: values closer to 1 indicate a weaker effect. The efficiency improvement is performed on the technosphere matrix only and the values of the efficiency improvement are randomly selected using a uniform and beta distribution, respectively, and in both the cut-off and consequential system models of the ecoinvent database.

as illustrated by the almost flat curve. This is because the battery has become by then a minor component in terms of mass, and a slight increase of its mass will not affect the driving mass or the electricity consumption of the truck in a significant manner.

Non-linearities in The Upscaling of The Bitcoin Mining Network

The results from the BAU scenario represent a linear growth of the Bitcoin mining network. However, in reality an expansion of such a network will result in changes in the geographical distribution of miners and in improvements in mining efficiency. In particular, **Figure 6** shows the impact of the network under the various scenarios considered in this study. It is clear from the figure how the Global Warming impact of Bitcoin mining heavily depends on where the miners are located — thus on which electricity mix they rely on.

An enlargement in the Bitcoin mining network leading to miners choosing new locations results in a potential increase in Global Warming impact by 31%. The upscaling also substantially depends on the mining equipment efficiency and shows a potential decrease in impact by 48% using current projections for more efficient mining equipment.

The combined upscaling effect of both changing the geographical distribution and of using more efficient mining machines results in a net decrease in impact by 32%. Based on the historical record of increasing efficiency and varying geography of the Bitcoin mining network, it is very reasonable to assume that over time there will be an improvement in mining efficiency (TH/sec increase) and that new facilities will not be installed at every existing location. Consequently, a linear growth model that does not take into account these factors would likely return inaccurate results.

DISCUSSION

Limitations of The Methods Used to Identify Non-linear Effects

It is important to address the validity of results both in light of the choice of methods and cases, and also how well they allow answering the research question of whether a non-linear effect can be observed for scalable and emerging technologies.

The first case is defined as theoretical because substantial simplifications were made in the simulation due to lack of information on the values of the efficiency improvement *c*. For example, in reality not all coal-based power plants will

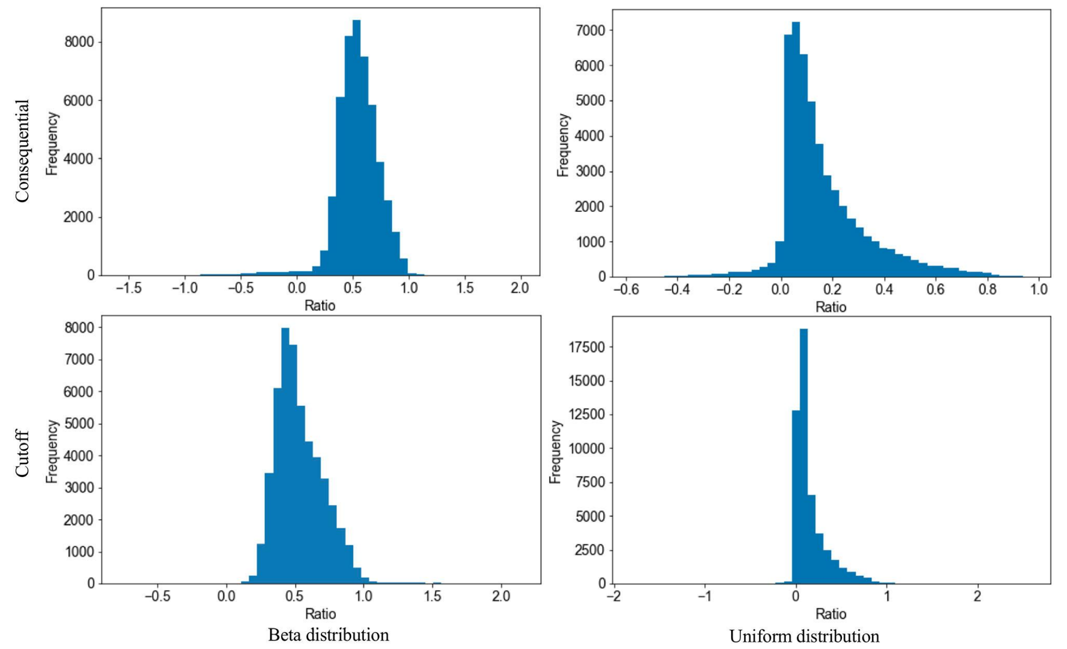

FIGURE 3 | Effect of efficiency improvements at database scale. The effect is obtained by randomly modifying the efficiency of all transformation activity datasets in the ecoinvent database and calculating the global warming impact for 50 randomly selected market activities. The effect is expressed as the ratio between the impact calculated using the improved datasets and the impact calculated using the unmodified dataset: values closer to 1 indicate a weaker effect. The efficiency improvement is performed on both the technosphere and biosphere matrices and the values of the efficiency improvement are randomly selected using a uniform and beta distribution, respectively, and in both the cut-off and consequential system models of the ecoinvent database.

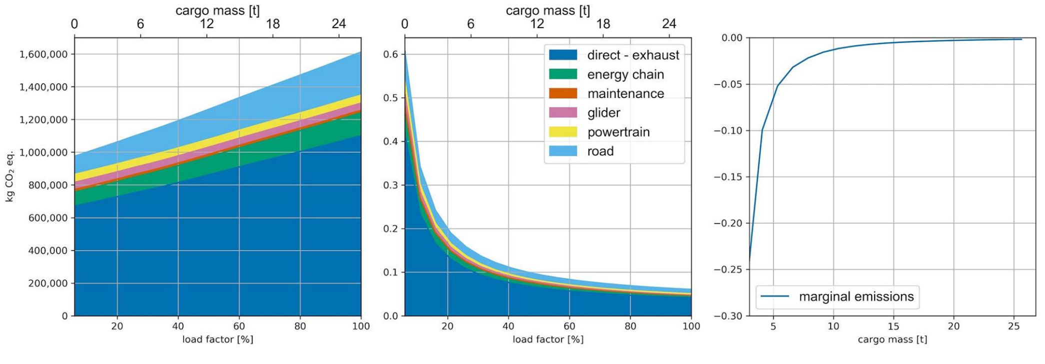

FIGURE 4 | Upscaling scenarios for transportation with a 40-ton diesel truck. Left: Total Global Warming impact in kg CO_2 -eq as a function of the capacity utilization. Center: Global Warming impact in kg CO_2 -eq/tkm as a function of capacity utilization. Right: Change Global Warming impact in kg CO_2 -eq/tkm as a function of cargo mass.

be improved in the same way (fixed *c*). Similarly, some improvements like fuel use and emission generation would be correlated and therefore using a different coefficient for each exchange of a *transformation* activity (randomly sampled instances of C_k) was also a simplification. These simplifications were however necessary to performing the simulation at the

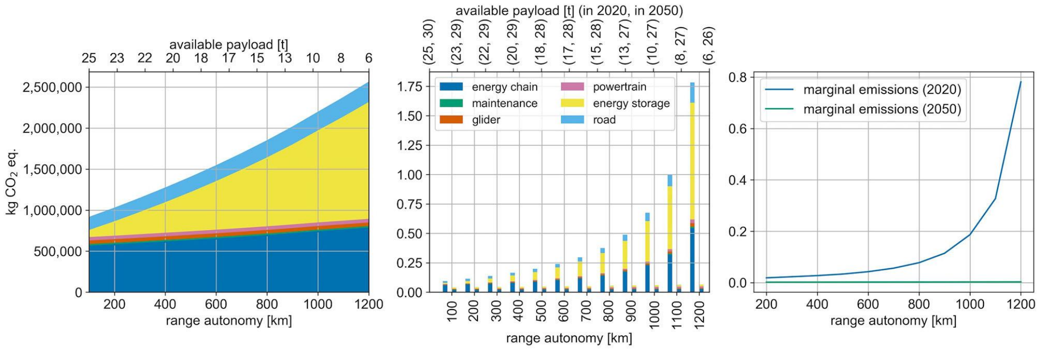

FIGURE 5 | Upscaling scenarios for a 40-ton battery electric truck Left: Total Global Warming impact in kg CO_2 -eq as a function of vehicle range autonomy in 2020. Center: Global Warming impact in kg CO_2 -eq/tkm as a function of vehicle range autonomy in 2020 and 2050. Right: marginal Global Warming impact in kg CO_2 -eq/tkm as a function of vehicle range autonomy in 2020 and 2050.

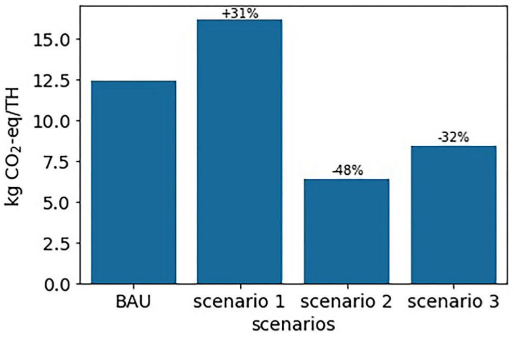

FIGURE 6 | Global Warming impact in kg CO_2 -eq/TH (Terahash) for different Bitcoin mining scenarios. BAU: Business as usual scenario (linear growth): Scenario 1: location-sensitive scenario. Scenario 2: equipment-sensitive scenario. Scenario 3: location- and equipment-sensitive scenario.

scale of the entire database, which was the primary purpose of the analysis.

When looking at the improvement of a specific activity such as coal-based electricity production the non-linear relation between changes in efficiency and changes in impacts is clear for single activities. The magnitude of this non-linear effect is activity-specific and therefore hardly generalizable at database level. Technological maturity is relative to time, thus the database is bound to have dated information, including when it comes to efficiency. It is, however, largely unknown to what extent the database fails to represent technologies at their highest technological maturity, and which specific flows can be improved in terms of efficiency.

When conducting the analysis at database scale, it is unfeasible to hand-pick activities or flows to selectively improve, and the stochastic approach remains the most pragmatic solution. An alternative approach could have been to selectively extract specific types of activities, for example all activities related to energy production or raw material extraction, or to specific sectors known to be highly impacting (e.g., energy, transportation, agriculture), and evaluate the effect of upscaling-related efficiency improvements in these groups. This could potentially result in more easily explainable relationships between the change in efficiency and the change in impact, but the validity of this conclusion would remain constrained by subjective selection of the groups of activities and would still remain difficult to generalize.

The choice of using a specific beta distribution for efficiency improvements is also subjective and was here presented in comparison with the choice of a uniform distribution. While assuming that all flows could be improved in any amount was considered an excessively unrealistic assumption, assuming that all flows could be potentially improved marginally seemed a more conservative and realistic one. It should be stressed that while to the best of the Authors' knowledge no information is available in literature on the observed distribution of efficiency improvements, previous studies in specific domains show that, in fact, efficiency improvements are usually of relatively contained size, e.g., 14–16% for CO_2-eq/kWh from wind power (Caduff et al., 2012).

Therefore, selecting random activities within the database and changing their efficiency is beneficial to provide an indication of the potential upscaling-related uncertainty. Even if a single relationship cannot be clearly generalized for all activities, the simulation provides evidence suggesting that globally, at database scale, technological upscaling on the impact of a system is in fact non-linear.

Regarding the transportation case, several assumptions were made. In the first example, a truck with a load factor ranging from 0 to 100% was considered. In reality, the load factor for trucks in Europe is rather constant and comprised between 20 and 40% for the size considered in this study (Eurostat, 2020). Trucks with a load factor below 20% or above 50% are not highly representative of the transport market. If the average load factor is in fact constant and always within the same range of values, one may not encounter the non-linear variations that have been shown here. In the second example, the most critical assumption is probably relating to the future development of battery technology and whether the energy density of battery cells will reach the value used for the year 2050. However, even if this assumption is inaccurate, it would not invalidate the non-linear relations observed.

The model of the Bitcoin mining network includes only parameters that directly influence the environmental impacts of Bitcoin mining. Such a model is not able to reflect the emerging technology's vulnerability to outside shocks such as changes of miner revenues like Bitcoin halving (Meynkhard, 2019), or legislative changes like restricting miner locations (Alvarez, 2018) that likely would also lead to non-linear changes in environmental impacts. Changes to miner revenues directly impact which locations are profitable. Both an increase and a decrease in miner revenues caused by large Bitcoin market price fluctuations or the Bitcoin halving can influence where new mining locations are opened. Legislative changes can also be important for modeling upscaling of Bitcoin mining. China's crackdown on China-based miners in 2018 is one example of legislative changes that influenced the mining locations of Bitcoin miners (Alvarez, 2018). These factors are not included in this model but can be relevant when modeling the impacts of the Bitcoin mining network and lead to further non-linear effects.

It is important to discuss the general validity of these findings beyond the cases presented here. While it is beyond the ambition of this work to provide a comprehensive overview of all possible cases of non-linearity in the LCA of scalable and emerging technologies, these cases are exemplary as they allow appreciation of several different facets of the non-linearity problem and thus address it in its complexity. In particular, the selection covered the non-linearity due to both foreground and background modeling assumption, both theoretical and concrete examples of non-linearity (considering several activities at once with low detail vs. one activity with high detail), and the non-linearity introduced by changes in the values of a model vs. the change in the structure of a model.

On the Relationship With Uncertainty and Sensitivity Analysis

Essentially, the present work can be interpreted as a study of uncertainty and sensitivity in the LCA models referring to a specific domain: technology upscaling and emerging technologies. It is thus relevant to draw a parallel between existing research on uncertainty in LCA and the current study.

The LCA literature on uncertainty is already mature, as testified by recent remarkable contributions where advanced probabilistic techniques are used to study the uncertainty of LCA models for current technologies (AzariJafari et al., 2018) or emerging ones (Mendoza Beltran et al., 2018a; Blanco et al., 2020), as well as more theoretical contributions (Bisinella et al., 2016; Cucurachi et al., 2016; Mendoza Beltran et al., 2018b). There are different ways of defining uncertainty, and for the LCA domain Igos et al. (2019) suggest classifying uncertainty either according to its intrinsic nature - epistemic or aleatory — or according to its location in a LCA model. In the latter case, one can distinguish between uncertainty regarding the structure of the model, the quantities used in the model, or the context in which the model is used. While some techniques like stochastic simulation allow quantification of the uncertainty associated with the output of a LCA model, techniques like global sensitivity analysis allow linking it to the uncertainty of the model inputs.

The uncertainties related to location are considered more closely here as they fit well to the analysis of the cases presented in this study and are also easily linked with other literature addressing uncertainty in models more generally (Saltelli, 2008). Briefly, while quantity-uncertainties reflect the unknowns associated with the specific value associated to a model parameter or input, model-uncertainties refer to the unknowns associated with how the model operates on these quantities, intended as how the different model parameter and inputs are combined together in a structure that provides a simplified representation of reality. Context-uncertainties refer to how the context of the decision affects the LCA modeling, and while they can be significant, they are not particularly relevant in the analysis of the specific cases presented in this study.

The simulation performed at database level by increasing efficiency for specific activities could be defined as a semi-Monte Carlo approach (Heijungs and Lenzen, 2014). This analysis targeted quantity-uncertainties specifically and disregarded model-uncertainties. The approach indeed has limitations as it is reasonable to assume that when upscaling a specific activity, some inputs would be replaced by others, for example when changing the material composition of specific components of the technology or shifting from one source of energy to another. This has been observed in previous studies, for example by Blanco et al. (2020) and van der Hulst et al. (2020). The simulation performed here was not able to take this sort of model-uncertainty into account and the conclusions provided here should be interpreted considering such limitation. Changes in the number and type of inputs of an activity might lead to possibly even more non-linear effects.

The case of the transportation model focuses again on quantity-uncertainty, investigating the effect of changes in the value of two specific model parameters: load factor and range autonomy. This is not a stochastic approach but could be intended as a simple local (one at the time) sensitivity analysis (Bisinella et al., 2016) showing how variations in their value leads to non-linear effects on the model output. In this case the interesting part is that a parametrized model is used to build a foreground inventory and therefore it is possible to study the non-linear effects of changing the quantity of one parameter at the time. Many LCA studies in fact operate similarly, as especially nowadays the domain of LCA has been enriched by the use of models taken from other disciplines (De Rosa et al., 2017; Pizzol, 2019). Thus, the case of transportation here presented is representative of those situations where a complex phenomenon - characterized by a dynamic and possibly non-linear element that nevertheless can be described in good detail with a parametrized model — is then simplified to generate a static life cycle inventory that is thus a snapshot of such complexity.

The LCA model of Bitcoin mining is dependent on data for mining locations and mining equipment use. This data is scarce and, in some cases, diverging. It is therefore important to highlight that this analysis and its results have an intrinsic uncertainty. These have been addressed in a previous study (Köhler and Pizzol, 2019) by conducting both a stochastic simulation and a sensitivity analysis for all parameters and providing an insight of the range of results and of which parameters most strongly influence the results. However, for the purpose of this study — addressing non-linearity of upscaling — this quantity-uncertainty is subordinate as it only influences the magnitude of results, but not the conclusion that upscaling the Bitcoin mining network does not lead to linear increases of impact.

Additionally, the scenarios are a projection of the future, and should therefore be considered an exploration of potential future impacts. In particular the location-sensitive scenarios provide insights on how changing the model structure influence the results and thus address directly the model-uncertainty. Here, not only the quantities (percentage of total mining performed in each location) but also the model structure (number and types of locations) are different from the BAU scenario. The equipment-sensitive scenarios focus on one parameter only, the efficiency of mining equipment, and thus address quantity-uncertainty directly. Due to its simplicity, considering the combined effect in changes of both location and efficiency via scenarios cannot be formally considered as a global sensitivity analysis (Saltelli et al., 2008) but is indeed a step toward this direction.

How Much Is Non-linearity a Problem?

What the present work suggests is that the uncertainties introduced by non-linear effects can be substantial and should be explicitly considered in the life cycle assessment of technologies that are emerging and not yet operating at scale. These findings confirm previous research on the uncertainties in the LCA of emerging technologies (Lacirignola et al., 2017; van der Hulst et al., 2020).

The non-linear effect of improving the efficiency of a technology can have unexpected consequences at database level, when considering all the upstream and downstream processes that are interconnected with the activities employing such technology. The non-linearity becomes critical when investigating the impact of new technologies that are energy and material intensive in their early stages, but also when forecasting the impact of existing mature technologies under different future technology scenario mixes, for example for energy production. The effect of upscaling specific activities, under the assumption that this upscaling returns higher efficiency — which is justified by examples in literature — might have an unpredictable and non-linear effect on the impact of a product system and of related product systems.

Using datasets that are built using data from pilot scale activities and are not representative of the potential of such activities at large industrial scale might thus skew results in unexpected ways. Broad and updated data coverage of the database used for the foreground modeling is thus of critical importance in LCA studies of emerging technologies. While database providers should naturally strive for data collection on unit processes that are as close as possible to a high maturity stage, the practitioner should model background systems that are relevant to the time when the system is modeled, to avoid temporal mismatch — as Arvidsson et al. (2017) point out. This study confirms this finding showing the non-linear effect that using an efficiency-improved version of the database might introduce and highlights the importance of considering background system changes in the assessment of emerging technologies. The feasibility and relevance of this approach has already been demonstrated in practice (Hertwich et al., 2015; Mendoza Beltran et al., 2018a).

In the case of the transport model, non-linear relationships between inputs and outputs of the truck model are less of an issue, as those linearities are in fact considered in both real life and current models. Hence, improving the engine efficiency of a vehicle by a factor of two will certainly not affect the fuel consumption to a similar extent in real life, and nor will it in the LCA model used, as fuel consumption is the result of complex interactions between components placed between the tank and the wheels of a vehicle (e.g., the engine, but also the gearbox, transmission shaft, wheels, etc.). In this case, the issue of non-linearity and the uncertainty associated to it lies outside the truck model and becomes more relevant when addressing future technological scenarios such as how the fuel cell suppliers and the energy efficiency of fuel cell stacks will develop as demand increases, and whether the lithium-ion based batteries will be replaced by a disruptive technology.

This study shows how using a linear assumption in the modeling of the Bitcoin mining network is a strong and excessive simplification of reality. In the location-sensitive scenario (Scenario 1), the impact per additional TH computed increases by over 30% compared to the BAU scenario, while in the equipment-sensitive scenario (Scenario 2), the impact decreases by almost half. In contrast, Köhler and Pizzol (2019) model upscaling scenarios for the Bitcoin mining network for early 2019 and show a decrease in the impacts for both their technology and equipment-sensitive scenarios. The location and equipment-sensitive scenario (Scenario 3) has 32% lower impacts than the linear BAU scenario. In Köhler and Pizzol (2019), the results from the location and equipment-sensitive scenario are 76% lower. It seems therefore to be especially important in the Bitcoin mining case to retrieve accurate data on where new mining facilities are installed and what kind of electricity they consume as the impacts can both decrease or increase per additional TH computed, depending on the assumptions on the geographical distribution of miners. This highlights the importance of building relevant scenarios when upscaling an LCA model for a product system where the structure is expected to change at different scales and levels of maturity.

CONCLUSION

By challenging the idea that product systems scale linearly, this work shows that non-linear effects should be explicitly considered in the life cycle assessment of technologies that are scalable or emerging. In these cases, a production activity will perform differently and with different efficiencies at different scales and levels of maturity, and its impact per unit of production output is therefore not fixed. Thus, the product system model should reflect the scale and technological maturity of the activities under analysis.

One innovation that this paper introduced is highlighting that — especially for the case for scalable and emerging technologies – the production output ($\boldsymbol{y}$) of an activity is a separately varying entity than the functional unit of a product system **f**. In mainstream LCA,

$$h = h(\boldsymbol{f}) \tag{8}$$

is a linear function (Heijungs, 2020). What is proposed here is instead that:

$$h = h\left(\boldsymbol{f}, \boldsymbol{y}\right) = h_1\left(\boldsymbol{y}\right) \cdot \boldsymbol{f} \tag{9}$$

where the dependence on $\boldsymbol{f}$ is linear but the dependence on $\boldsymbol{y}$ is not, as $h_1(\boldsymbol{y})$ is a non-linear function.

While the LCA is only linear in terms of functional unit dependence, the coefficients that define each activity (values used in **A** and **B**) are based on the technologies as the practitioner defines them. In this sense, the use of parametrized LCA is one useful way of modeling systems that exhibit non-linear properties. In this respect, Heijungs (2020) already observes that *"the whole idea of parametrized LCA obviously deserves a more rigorous treatment"* and the results of this study strengthen this hypothesis and make steps forward in this direction. However, cases such as the Bitcoin network one here presented show that not all non-linearity problems can be addressed by only changing parameters in one single model structure, as it is expectable that system upscaling will influence the type of inputs needed to generate the production output, and this will require changing the structure of the LCA model (number and type of activities and exchanges in $\boldsymbol{A}$ and $\boldsymbol{B}$).

The study has also shown that addressing non-linearity is essentially a matter of addressing uncertainty in LCA models, and therefore classic uncertainty and sensitivity analysis techniques can be used effectively to investigate and highlight non-linearity. These include, for example, stochastic simulation, developing and assessing scenarios, and studying the effect of a change in output due to a change in specific inputs.

There is currently great attention and expectations to the role of new innovative and emerging technologies for the sustainability transition. The study of the environmental benefits of these technologies is challenged by the availability of pilot-scale data only, and inevitably requires the use of assumptions and the generation of scenarios, and therefore is characterized by intrinsic uncertainties. This study has shown that non-linearity is definitely an uncertainty issue in the study of new technological developments and their impact. Thus, future studies operating in this line of research are strongly encouraged to manifest an explicit awareness of where technological upscaling could occur and to address potential non-linearity issues as part of the uncertainties, and the examples provided in the present work can ideally provide a good inspiration for both identifying and addressing non-linearity.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found at the online repository: https://github.com/massimopizzol/non-linearity-LCA. The repository is archived on Zenodo (Pizzol et al., 2020).

AUTHOR CONTRIBUTIONS

MP contributed with the initial original idea and coordinated, supervised and quality-checked the entire research effort, and contributed to perform the ecoinvent simulation. RS contributed to the ecoinvent simulation and performed the entire transport simulation. SK performed the entire bitcoin simulation. AA contributed to the ecoinvent simulation and wrote the initial paper draft. All authors contributed to the writing and revising of the manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frsus.2020.611593/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

ARTICLE IV

Köhler S., Pizzol M., Sarkis J. 202X. "Unfinished Road – Blockchain to Sustainability in Supply Chains". In *Frontiers in Blockchain*.

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Abstract
Blockchain technology has been promised as a solution to social and environmental issues in supply chains. The potential includes reduction of vulnerable party exploitation and avoiding environmentally harmful practices. Yet, it remains unclear how these potential improvements are created and whether blockchain can truly contribute. Therefore, this field study explores and identifies the mechanisms for blockchain technology to facilitate positive social and environmental impacts in supply chains. We applied a grounded theory approach and interviewed blockchain technology implementers and practitioners that allowed a detailed analysis of this problem despite the scarcity of practice data. The results include the development of a middle-range theory that shows barriers and drivers of blockchain-based technologies in supply chains, introduces the concept of blockchain-enabled system, and outlines expected outcomes and impacts. We further identify four impact pathways that describe how blockchain-enabled system create positive impact: (voluntary) market mechanisms, plausibility checks, smart contracts and tokenisation, and peer-to-peer trust. The study contributes by providing insights into "how" blockchain-based technologies in supply chains can lead to social and environmental impacts. The study also furthers the discussion on blockchain technology's role in supply chain implementation and addresses the yet unresolved problem of measuring the impact of such blockchain-enabled systems.

Keywords: traceability, digitization, impact, responsible production, responsible consumption, blockchain, supply chain

Unfinished paths – from blockchain to sustainability in supply chains

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1. Introduction

Globalisation has made modern supply chains increasingly complex as technology, culture, and value chain activities become entwined and supply chains reach deep into various regions of the world. Companies often do not know their tier three or four suppliers; with limited visibility beyond the first tier. Similarly, producers do not always know who consumes or manages the materials they supply. Information flow and visibility between these and other actors in supply chains is low. Thus, identifying product or material sourcing and process activities that include questionable and illegal practices including human rights abuses, environmental damage, or fraud is extremely difficult (Clarke and Boersma, 2017). Blockchain technology proclamations include the ability to solve the problem of lack of trusted information from supply chains and consequently increase visibility (Feng et al., 2020; Wang et al., 2019b). In short, blockchain technology is a decentralised add-only ledger that makes it virtually impossible to change data that has been entered. In supply chains, blockchain technology is implemented together with other components – such as tracking technologies – to address issues of traceability (Köhler and Pizzol, 2020).

These blockchain-based technologies in supply chains can bring advantages in terms of transparency and efficiency (Köhler and Pizzol, 2020). Based on their recent literature review, Lim et al. (2021) state that there are three major aspects that blockchain technology improve current supply chains: shareability, security, and smart capabilities. Some of the most prominent potentials in that respect include preventing data fraud, eliminating intermediaries, reducing time and cost of transactions, enabling secure data sharing, and automating processes (Lim et al., 2021). For example, IBM and Walmart implemented a blockchain-based traceability system for mangoes that reduced the time for tracking product origins from seven days to 2.2 seconds (Kamath, 2018). In another project, Maersk and IBM collaborated to increase efficiencies of international supply chains by using blockchain technology to securely share data among trading partners and replace hardcopies with digital records (Kouhizadeh et al., 2020). Blockchain-based technologies together with other technologies are expected to become the standard for tracing and sharing product-related information (Kopyto et al., 2020).

One interesting statement in the latest review of blockchain applications in the supply chain by Lim et al. (2021) is that "*the discussion on sustainability seems to be limited compared with other subthemes*". They further note that there is no research that systematically proposes a sustainable supply chain performance model using blockchain technology (Lim et al., 2021). This suggests that the research on sustainability of blockchain-based technologies in supply chains is currently underdeveloped. While there are numerous studies exploring the potential of blockchain-based technologies in supply chains (Azzi et al., 2019; Rejeb et al., 2020), only very few focus explicitly on sustainability. Kamilaris et al. (2019) identify among other points the potential of blockchain technology to support small farmers, create a platform for emission reduction efforts, reduce fraud, and generate consumer awareness. (Kouhizadeh and Sarkis, 2018) highlight that trusted information and visibility provided by blockchains can support purchasing decisions and selecting sustainable products. They further point out that verified data on blockchain can provide better input and output data for eco-design and life cycle assessment facilitating more sustainable production (Kouhizadeh and Sarkis, 2018).

A close examination of this literature indicates that while existing studies explore and identify what potential benefits blockchain technology in supply chains *could* bring, they do not address in-depth *how* such positive impact will be reached. This becomes apparent when looking at how the studies describe the potential. Kamilaris et al. (2019), for example, discuss a “hypothetical scenario” in which a cooperative uses a smart contract to conduct sales of their cereal production and uses auxiliary verbs such as could or might to describe the potentials. Similarly, Kouhizadeh and Sarkis (2018) use verbs such as may throughout their study to illustrate blockchain potentials in supply chains. They further highlight that they have only scratched the surface of the role of blockchain in sustainable supply chain management. There is limited empirical evidence of the fulfilment of these potentials.

Thus, while other fields of research such as big data and developmental studies have consolidated an understanding of the pathway from decisions and actions made to impact on specific endpoints (Dubey et al., 2019; França et al., 2020; Jørgensen et al., 2010; Olney et al., 2009), this has not been investigated for blockchain-based technologies in supply chains. A social science approach can be valuable to address the research question of how to achieve positive impact from blockchain technology – especially in early blockchain technology adoption stages (França et al., 2020).

Therefore, the purpose of our study is to discover the mechanisms by which blockchain-based technologies in supply chains create positive social and environmental impact. Given early and only emergent understanding in this field of study and with limited explanation – theoretically or practically – of how blockchain-based technologies in the supply chain create positive impact, a grounded theory approach is taken. Blockchain-based technology experts, the majority of whom have first-hand experiences implementing the technology in the supply chain, are interviewed. This information provides first-hand insights from some of the few cases that have seen actual blockchain implementation. Since blockchain-based implementations in supply chains are still in early development stages, it would be unrealistic to provide a conclusive explanation of this phenomenon. Thus, we intend to propose a "middle-range theory" that is context specific and should be further tested and adjusted over time (Craighead et al., 2016). This explorative study aims to address the following research questions:

- How and by what mechanisms do blockchain-based technologies in the supply chain lead to positive social and environmental impact?
- What is the role of the blockchain component in the supply chain that generates this impact and can this component's contribution be separated from the impact generated by other components?

The study contributes to and advances the existing body of knowledge in several ways. Where previous studies mainly focussed on blockchain-based technology impact (Lim et al., 2021), we develop a middle-range theory on how blockchain technology implemented in supply chains creates impact. Additionally, we describe four specific impact pathways. Second, we further discussion blockchain's role in supply chain operations. Köhler and Pizzol (2020) highlight the importance of taking a systemic perspective – we add to this perspective by evaluating whether blockchain technology can be investigated separately and by highlighting the importance of the system architecture design. Finally, we emphasise early impact measurement while determining the potential of implementing blockchain technology. The actual implementation effects need to be tracked and measured in order to verify the potentials and understand the extent these potentials are met.

2. Materials and Methods

For this study a grounded theory approach was used, defined as a qualitative research approach that generates a general explanation of a process, an action, or an interaction arising from the views of relevant people (Creswell and Poth, 2018). The explanation should be grounded in the data from, for example, interviews. Since the implementation of blockchain-enabled systems is still in the early stages, their impact cannot yet be fully known and measured. A conclusive explanatory theory of the blockchain-impact nexus is thus currently beyond reach. Instead, we propose here a middle-range theory defined as a conceptualization to a specific context (Craighead et al., 2016). In our case, we derive a conceptual scheme that serves as an explanation to how blockchain-enabled systems in supply chains currently create impact and how experts believe they will create impact in the future. As blockchain-enabled systems advance and are implemented for longer periods of time, the conceptual scheme – our middle-range theory – needs to be tested and may need to be refined. This explorative approach was chosen since there are no previous studies of how blockchains implemented in supply chains generate sustainability impacts. Figure 1 provides an overview of the research procedure.

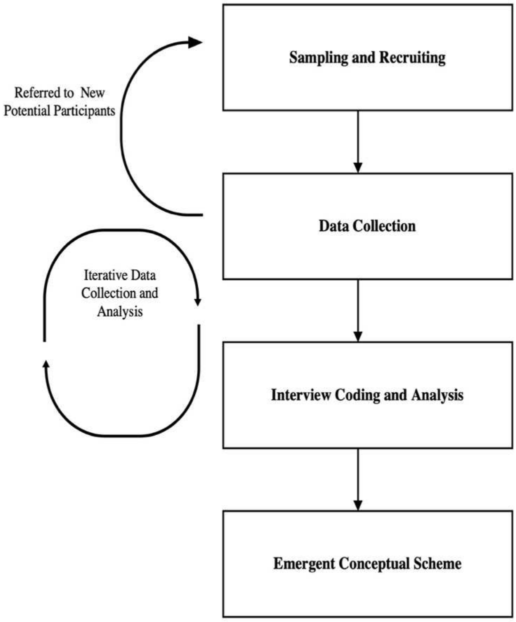

Figure 1: Research procedure. The research procedure started with sampling and recruiting study participants before conducting interviews. From some interviews new study participants were identified. The interviews were then individually coded before all quotes belonging to one theme were grouped. The interview and analysis process proceeded iteratively until theoretical saturation was reached meaning no new information was gathered from the interviews. Finally, a conceptual scheme was derived from the themes that emerged from the interview data.

2.1 Participant sampling strategy

We used both theoretical sampling and snowball sampling in this study. In theoretical sampling, participants are selected based on leads in the data (Reilly et al., 2012). For this study, we sought individuals who had first-hand experiences in developing and implementing blockchain-based technologies in supply chains. We specifically did not focus on a single sector and were interested in speaking with different actors including technology developers, brands, consultants or other actors in the supply chain. Theoretical sampling is an iterative process. Based on the results from already conducted interviews, new participants can be identified. In theoretical sampling researchers move back and forth between sampling, data collection, and analysis until data saturation is reached or no new information is collected with new interviews (Tie et al., 2019). We also used snowball sampling. At the end of each interview we asked study participants for additional participant suggestions (Naderifar et al., 2017). Since the study participants typically have contacts in their field, they were able to bring other experts to our attention that we otherwise may have missed.

In total, 16 interviews were conducted. Of the study participants 63% were technology providers, 19% were actors in the direct supply chain, and 19% were other actors such as consultants. 44% of the participants worked on projects in the agricultural sector, 31% in the mining sector, and 25% in the fishing sector. 50% of the interviews were CEOs of which all but one were also the (co-)founders. 22% of the study participants were more technical including chief technology officers and one developer. The remaining participants were from marketing, procurement, product management, and consulting. The study participants come from more than 10 different countries with the majority of them (69%) now being located in central Europe (Netherlands, Germany, England).

2.2 Interview procedure

We conducted semi-structured interviews (Kallio et al., 2016). They allowed us to gain detailed information on each implementation, and at the same time dive deep into factors shaping them. It further allowed us to adapt the interview to learn more about participant specific experiences and knowledge. For example, if one study participant mentioned that they will add a specific feature for the next version of their implementation, it was asked if they could talk more about this feature.

We sent interview invitations via e-mail accompanied by a signed invitation letter. In some cases, one reminder was sent. If the contacted person agreed to be interviewed, a call was scheduled, and the interview guide was sent in advance. The interview typically started with an introduction of the interviewer and the project before asking for consent to audio record the conversation. The interview questions were not necessarily asked in the order presented in the interview guide and not necessarily all questions were asked depending on how relevant they were for the specific interview. Additional questions may have been included such as “You mentioned efficiencies. In what ways does blockchain help?” in order to get more detailed answers.

The study participants had the chance to ask questions about the project and the purpose of the study. The interviews were typically conducted via video call and lasted between 30 and 45 minutes. The interviews were audio recorded with the consent of the participants and then transcribed. Prior to analysis, all identifying information was removed from the transcripts. All interviews were carried out between April 2020 and September 2020. The interview guide (SI.1) can be found in the supporting information.

2.3 Interview analysis

The interview analysis was completed using a "quote by theme" matrix and using anonymised transcripts. A qualitative content analysis was completed in order to identify common themes. The analysis was an iterative process and is comprised of different coding rounds until a satisfactory combination of themes was found (Gioia et al., 2012). It was considered satisfactory when the themes did not overlap and allowed for an explanation of the story across all the interviews.

In the first round of coding, three interviews from participants of different industries – agriculture, fish, and mining – were used to establish a first collection of codes. These codes were then grouped into themes. Subsequent interviews were then coded using the themes only, adjusting them and adding new ones as deemed necessary.

Relevant quotes from each interview were selected and for each quote the theme was identified. One quote could address several themes. All quotes belonging to one theme were put in a table and analysed to extract a summary for each theme. The set of themes could then be grouped into dimensions and were then displayed in a scheme summarising the results. Examples of coding is provided as Supporting Information (SI.2).

3. Results

The interview data shows that the supply chain implementation of blockchain-based technologies remains in its early stages. While three quarters of the study participants have implemented their blockchain-based technologies, all of the study participants are still improving their implementations.

3.1 How blockchain-enabled systems create positive impact

Figure 2 summarises a conceptual structure that we developed inductively from the analysis of the interview data. The coded interview data was condensed into themes through an iterative process, until reaching saturation. The themes were further grouped into dimensions shown as white boxes in Figure 2. Each dimension and theme is described in the following discussion.

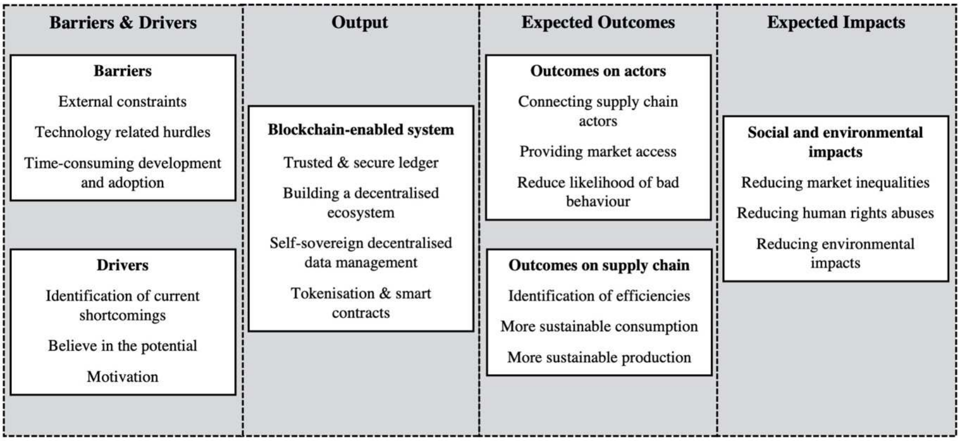

Figure 2: Outputs, outcomes, impacts, and factors influencing blockchain-enabled systems. The grey columns resemble a pressures, practices, and performance framework (Choudhary and Sangwan, 2018) where barriers and drivers represent pressures, the output is the practice, and outcomes and impacts are performance. The columns for practice and performance also illustrate an output, outcomes, and impacts approach (Koontz et al., 2020). The output is the decision taken to implement a blockchain-enabled system. The outcomes are the changes directly resulting from the output. The social and environmental impacts are changes on human wellbeing and ecosystem wellbeing – including reductions of existing issues. The white boxes represent dimensions. The bullet points summarise the themes.

We firstly introduce and define the concept of a *blockchain-enabled system* that emerged from the interview data analysis**.** A blockchain-enabled system is a system of technologies that uses a blockchain platform to securely manage supply chain data and connect supply chain actors. It is the underlying system of technology enabling positive impact. We then describe how the concept of blockchain-enabled systems is central to and relates with the other elements of our conceptual structure.

3.1.1 Barriers of blockchain-enabled system adoption

This dimension comprises factors that influence the adoption – or lack thereof – of blockchain in supply chains. *External constraints* to blockchain-enabled systems include a lack of digitisation, social and political instability, and a lack of standards and policies for implementing blockchain-enabled systems.

Technology related barriers refer to blockchain technology immaturity. Some examples of this immaturity include limitations in transaction speed and transaction costs. Governance was also identified as a barrier as *"people find a decentralised reality very uncomfortable"* and finding agreement across supply chain actors can be time-consuming with no guaranteed consensus causing further delays in decisions and operations.

Time-consuming development and adoption refers to implementation processes that can take a long time requiring substantial resources. For example, digitisation of paper-based processes and the development of trust among actors.

3.1.2 Drivers of blockchain-enabled system adoption

This dimension includes factors that influence and drive implementation of blockchain-enabled system. *Identification of current shortcomings* refers to the process of isolating existing problems such as diffused and opaque supply chains where little is known about the product journeys or suspecting that the supply chain actors may behave unethically or illegally – for example, human rights violations. Study participants identified the need to move beyond existing centralised solutions resulting from past negative experiences or the need to develop a traceability solution given that they had no existing ones. Other driving factors include the lack of trust and communication in the supply chain and sometimes within their own organisations. Another driver factor is the desire of improving operational inefficiencies that caused delays of payments and shipments. Counterfeit products in the supply chain were also considered a major issue by some study participants. Study participants felt that current systems provided limited data, even for sustainability measures such as product-specific carbon footprints. Knowing true product sustainability characteristics such as product carbon footprints or human rights compliance are needed by companies to truly differentiate products beyond price and quality.

We observed a strong *belief* among study participants in the potential of blockchain-enabled systems that championed many characteristics. *"It's the future. Embrace it now or embrace it later."; "For me, it's the next step of human evolution after the internet."; "I think it could be revolutionary in the way that supply chains work"; and "The future world is decentralised. It is inevitable."*

The third major driver theme we identified is *motivation*. Study participants had differing reasons for implementing a blockchain-enabled system in their supply chain: to gain competitive advantages by helping to improve their reputation through building this capability; to protect their brand against supply chain risk; to ensure compliance with regulation; to build a system that is not owned by one entity and creating a platform that competitors want to join and where they feel safe to share data.

3.1.3 Blockchain-enabled system

Blockchain technology provides a *trusted and secure ledger* which creates trust in no-trust environments through its immutability.

Blockchain-enabled systems support *building a decentralised ecosystem* where not one person or entity owns the platform, with many actors involved in its data sharing and management. Blockchain-enabled systems provide a platform for collaboration such that everyone benefits from the data visibility. However, this is also the biggest challenge – finding a governance model that works for everyone involved.

Blockchain technology allows *self-sovereign decentralised data management*. Participants maintain the ownership of their data and then they can decide who gets access and the type of data to share. This is one of the key advantages of such a system mentioned by the study participants.

Tokenisation and smart contracts allow for automated and faster transactions and payments, which in turn creates liquidity and removes time delays for payments. Tokens – a representation of money, digital items, or real-life objects – further facilitate the connection of consumers and producers through tip-your-farmer schemes, micro-lending, or crowdfunding. It represents an easy and efficient way for payments and incentives to be traded globally.

3.1.4 Outcomes on actors

This dimension comprises the supply chain actor outcomes from implementing blockchain-enabled systems. Blockchain-enabled systems *connect supply chain actors*. Every actor's voice has the possibility of being heard and a peer-to-peer network can supplement or even replace some official systems.

Blockchain-enabled systems can *provide market access*. *"Nobody can stop you from getting in"* as one of the study participants framed it.

A decentralised trusted ledger *reduces the likelihood of bad behaviour*. Mistakes, fraud, and other bad behaviour can more easily be detected on the blockchain and will disincentivise such behaviour. Some bad behaviour could become significantly more difficult to complete – such as using a sustainability certificate for a larger amount that it was granted for.

3.1.5 Outcomes on the supply chain

This dimension encompasses the outcomes on the supply chain from implementing blockchain-enabled systems. *Efficiencies* arise from implementing blockchain-enabled systems through automating payments and contracts, while simplifying processes such as entering a country through a port. These efficiencies save time and money.

Blockchain-enabled systems incentivise *more sustainable production*. This is based on the assumption that companies either care enough about sustainable supply chains or are held accountable for their supply chains. Companies can use trusted and accessible data on environmental and social hotspots in the supply chain provided by blockchain-enabled systems. Companies can specifically support supply chain actors, ask suppliers to reduce impact, and criteria such as carbon footprints can become procurement conditions – incentivising greener practices.

Blockchain-enabled systems provide incentives for *more sustainable consumption*. The assumption is that having more specific and trusted information allows consumers to make more informed decisions. Blockchain-enabled systems allow for closer interactions between consumers and producers – even down to individual farmers in agriculture supply chains. Micro-loan schemes, tip-your-farmer schemes, or buying coffee from a specific lot drives loyalty among consumers.

3.1.6 Social and environmental impacts

We categorised the social and environmental impacts from implementing blockchain-enabled systems into three themes. These themes reflect participant expectations only, as the impacts have yet to be measured.

Reducing market inequalities include lowering inequities through increased access to markets and financial services for vulnerable supply chain actors. For example, blockchain-enabled systems can support circumventing traditional systems including banking or property registration, for instance by providing access to banking for those who are currently outside formal financial systems.

Blockchain-enabled systems can provide trusted and accessible information about product production including labour conditions, which can support the reduction of *human rights abuses*. Having visibility of this information allows companies to improve working conditions within their supply chain. With this information consumers can more easily identify products certified to not contain human rights abuses; allowing consumers to make more informed buying decisions. This activity puts pressure on actors who do not provide this information or do so inaccurately. Fairer prices for good actors incentivise good behaviour such as paying a living wage or investing in health insurance for workers.

Reduction of environmental impacts can also be supported by blockchain-enabled systems. Knowing where impacts occur allows supply chain actors to address these concerns. Buyers can directly support supply chain actors in reducing impacts, can incentivise good behaviour through including environmental impacts as a purchasing criterion, and consumers have better information to make buying decisions.

3.2 Impact pathways and mechanisms

Based on the analysis of the interview data we derived several possible impact pathways for a blockchain-enabled system to create positive impact. We then identified four mechanisms underlying the impact pathways: (voluntary) market mechanisms, plausibility checks, smart contracts and tokenisation, and peer-to-peer trust. Key examples of these impact pathways and mechanisms are illustrated in Figure 3.

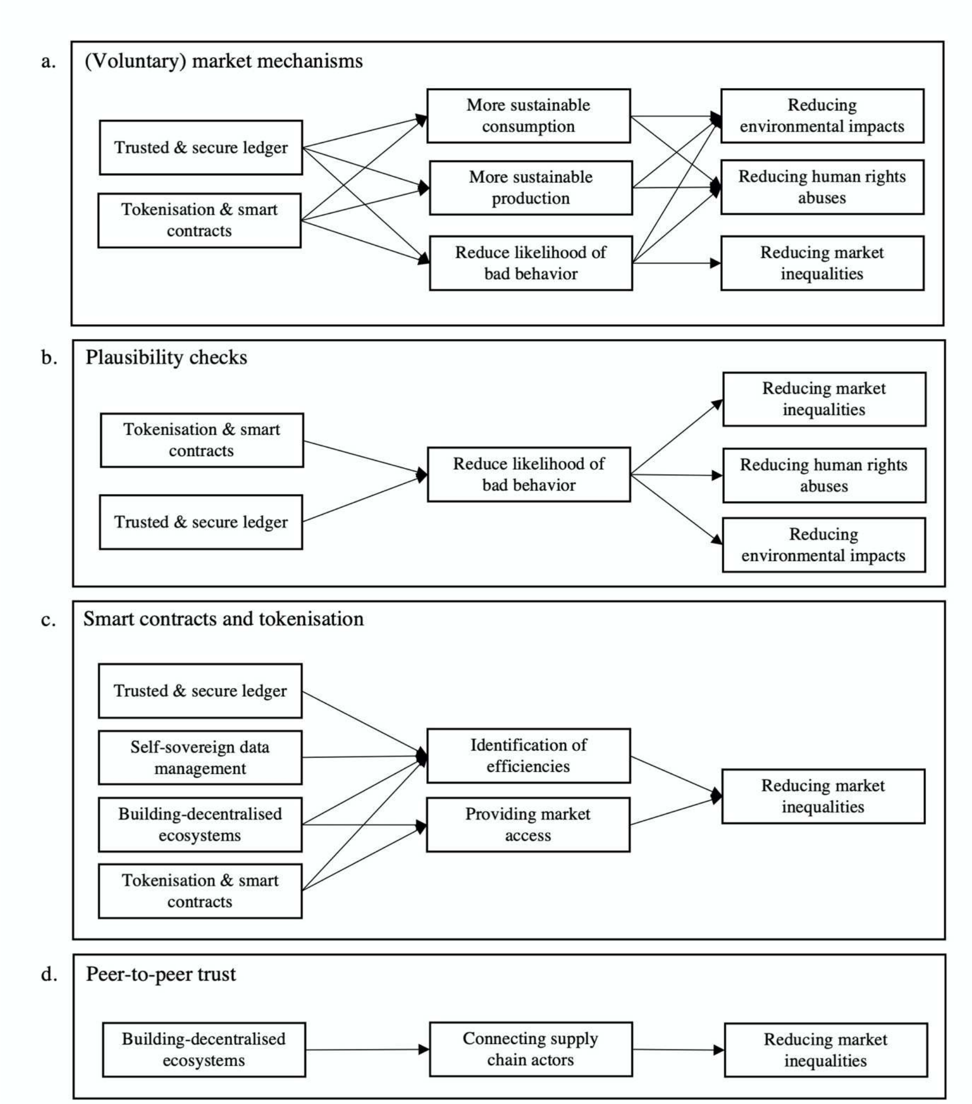

Figure 3: Impact Pathways and Mechanisms. Four mechanisms creating positive environmental and social impact have been identified. They are depicted in boxes a – d. Within each box it is shown how the outputs (first column) influence the outcomes (middle column) and how the outcomes influence the resulting impacts (last column). The arrows link these boxes portraying impact pathways.

3.2.1 (Voluntary) market mechanisms

These mechanisms are based on obtaining trusted information about products that can be verified by third parties. This mechanism is facilitated by blockchain-enabled systems and can allow consumers to access specific product information such as product source and processing characteristics. Accessible traceability creates transparency and can be a market differentiator for sustainable product markets, increase consumer engagement, and build loyalty. Study participants believed that consumers could make better and more sustainable decisions based on this accessible and trusted product information.

Similarly, companies may gain additional access to supply chain and product information that was previously opaque to them; in this way the blockchain-enabled system is able to reduce information asymmetry. In these systems companies can make buying decisions beyond standard price and quality business dimensions. Companies can more easily expand decision and management criteria to include human rights abuses records or carbon footprints of products and supplier processes. Companies can further take actions to increase sustainability by knowing the environmental and social hotspots in their supply chain. For example, an action would be to directly support supply chain actor improvement or by paying premiums for reducing sustainability impact.

In general, study participants argued for a positive transparency spiral leading to "*squeezing out bad actors"* over time, where initial supply chain actors collect and share supply chain data to make some information transparently available resulting in pressures for other supply chain actors to follow suit. In this situation, as more information becomes visible bad behaviour such as fraud or human rights abuse will see the "light of day". Actors displaying such bad behaviour are either removed from the supply chain or have severely limited market access. It is important however to highlight that this is still a conjecture by the respondents, as these results remain to be seen in practice. Policies supporting transparent and responsible supply chains will likely facilitate this development.

3.2.2 Plausibility checks

Another mechanism leading to positive environmental and social impact relates to employing validation algorithms for complex data. These validations can ensure that production volumes remain accurate or that certificates are not double counted or over the dedicated amount. Blockchain-enabled systems ensure that the data provided by supply chain actors such as farmers or processors cannot be manipulated or reverse engineered, especially proprietary information. After an asset is registered on the blockchain only the specific item registered can be used within the supply chain. The amount cannot be multiplied or unreasonably changed at a later stage. This makes both fraudulent behaviour and honest mistakes less likely to occur.

Machine learning algorithms were mentioned by one study participant as a tool to identify anomalies that humans would potentially not catch and that could lead to identifying other bad behaviour. These machine learning algorithms can be ingrained in blockchain smart contract-like systems.

3.2.3 Smart contracts and tokenisation

Interviews supported the ability of blockchain-enabled systems to achieve positive impact through automation and the use of tokens. One respondent provided an example:

"The other aspect of blockchain that we looked into […] is the potential of smart contracts to play a role. Where transactional agreements can be executed without an exchange of paperwork and signatures. [Actors in the supply chain] were able to conduct in a matter of two and a half hours a transaction that normally would take 10 days to complete."

Automating processes – such as payments upon execution of contracts – can speed the collection of data and create incentives for transparency by saving time and money. This kind of automation of payments further creates liquidity for supply chain actors as delays in payments are significantly reduced. This mechanism especially supports poorer actors such as farmers where a lack of funds can prevent them from participating in the market.

Tokenisation can be a valuable mechanism for connecting consumers with producers. Example schemes include *tip-the-farmer* and *micro-lending* activities. These mechanisms may also increase consumer engagement, in turn leading to more sustainable consumption.

3.2.4 Peer-to-peer trust

Building decentralised networks can support actors – especially in the Global South – that don't have an official identity, access to bank accounts, or other official documentation (World Bank, 2019). Providing decentralised identities that securely keep a record of individual activities and are not part of existing formal systems, such as bank transactions, can facilitate individual participating in the business ecosystem.

Blockchain-enabled systems could capture transactions, for example those that are conducted after receiving money through micro-loans from consumers. Using a blockchain-enabled system allows individuals that are disadvantaged to circumvent some existing systems such as banks; this approach can reduce barriers for market entry for these vulnerable actors.

4. Discussion

Blockchain-enabled systems in supply chains can potentially result in a variety of positive social and environmental impacts. These can happen through (voluntary) market mechanisms, plausibility checks, smart contracts and tokenisation, and peer-to-peer trust.

Market-based certification schemes such as FairTrade or Forest Stewardship Council (FSC) use (voluntary) market mechanisms in similar ways. These instruments work on the assumption that consumers are willing to choose more sustainably-produced products, which encourages competitors to follow this practice (Swartz et al., 2017; Taylor, 2005). This virtuous cycle can eventually push less sustainable products out of the market (Grankvist et al., 2004).

An increase in market shares of sustainably certified products over the past few years (Bullock and van der Ven, 2020) indicates that these market mechanisms work as consumers shift to certified products increasing the money invested in sustainable production. However, literature shows mixed results regarding the impact of certification schemes on reducing social and environmental impacts (Santika et al., 2020).

4.1 The role of blockchain in creating positive impacts

We asked if the impacts are due to the blockchain component in a system of technologies or due to other factors. The interviews provided only a partial answer to this question. We were able to determine that there are several reasons why study participants chose a blockchain-enabled system over a centralised one. Among these reasons we find negative past experiences, previous unsuccessful implementation of a centralised traceability solution for the company's business, and previous centralised technology providers that exploited the company's dependency on the providers' services to put pressure on the company.

According to the study participants another concern with a centralised solution is the difficulty with getting competing actors to participate in such a system. As one of the participants stated, they would not join a centralised system where they are not the host and not in control. Maintaining ownership of their data is another reason why blockchain-enabled systems are preferred by some actors.

It was further stated that using blockchain-enabled systems may mean that some companies are willing to allocate a larger budget for traceability solutions. This budgetary increase may occur since in some cases the funding for a blockchain-enabled traceability system comes from the innovation budget and not from the sustainability or a back-office budget. Thus, using a blockchain-enabled system can be a driver for implementing traceability systems and digitising supply chains through innovation channels.

However, based on the overall information retrieved from the interviews it was not possible to clarify to what extent the outcomes and impacts identified in this study are due specifically to the blockchain component in the systems analysed. It is also conceivable that determining if and to what extent outcomes and impacts are due to the blockchain component is in fact infeasible. Many technologies are interlinked in a system and the outcomes and impacts are generated from the emergent behaviour of such a system making it difficult to parse contribution by a specific technology. This observation means the overall system design and integration, not just the blockchain component, is of tremendous importance for achieving positive outcomes and impacts.

4.2 Measuring impact

Most study participants were not able to provide an answer to how they measure impacts of implementing a blockchain-enabled system, their justification being that it is too early to measure impacts.

What became clear is that different participants have different key interests – key performance indicators – in what needs to be measured. While some are interested in looking at increasing incomes of farmers, others are concerned with reducing human rights abuses and environmental impacts. Others were interested in consumer engagement and cost reductions. Thus, choosing relevant indicators for measuring impact is important as is the choice of an appropriate method to assess the relevant indicators. It may be advisable to consider indicator development early in blockchain-enabled system design so that pertinent information could be collected automatically.

We find it concerning that only a few study participants had thought concretely about measuring impacts as it makes it difficult to evaluate the success of their own projects and its potential continuation, further development, or dissolution. The lack of performance measurement might hinder the transfer of knowledge to other projects within a company or outside of it. This information is likely needed if positive impacts should be replicated and scaled.

4.3 Comparison with previous studies

In this study, we focus on how blockchain-enabled systems can bring positive social and environmental impacts, whereas other studies emphasise what kind of benefits blockchain technology in supply chains can have (Kamilaris et al., 2019; Kouhizadeh and Sarkis, 2018). While we propose a middle-range theory that should further be refined and tested, our findings are based on insights from cases that have seen actual implementation. This permits not only a detailed analysis, but also a realistic assessment of the current status-quo of blockchain-enabled systems and how they lead to positive impact.

This study confirms previous findings that blockchain technology can increase trust and transparency (Galvez et al., 2018; Köhler and Pizzol, 2020) and use them to facilitate positive social and environmental impact. Many of the outcomes described in this study are also mentioned in previous literature. For example, Kamilaris et al. (2019) mention both increased consumer awareness which relates to the theme of *more sustainable consumption* as well as reducing fraud which describes part of the theme *reducing the likelihood of bad behaviour*. Similarly, Kouhizadeh and Sarkis (2018) describe several components of the theme *more sustainable production*. This present study provides in contrast to previous literature a comprehensive overview of how positive social and environmental impact can be created with blockchain-enabled systems in supply chains including descriptions of four specific mechanisms based on insights from practice. The study further supports previous findings that the design of blockchain-enabled systems is important when implementing blockchain technology to achieve specific sustainability objectives (Kewell et al., 2017; Saurabh and Dey, 2021).

4.4 Limitations and validity of the qualitative methodological approach

We discuss here potential sources of bias due to the choice of respondents and more broadly the use of a qualitative and grounded theory approach.

The findings of this study are based on the information provided by 16 interviews with experts on blockchain-enabled systems in supply chains including technology developers, actors in the supply chain, and consultants in the agricultural, fishing, and mining sectors covering a broad range of actors and sectors. Considering the still nascent and thus small industry of blockchain-enabled systems in supply chain 16 interviews with experts holding key positions within their organisations was considered satisfactory.

Information saturation was reached, meaning that new interviews were carried out until no substantially new information was generated, and therefore the number of interviews was considered sufficient to gather all the relevant knowledge on the subject. The validity of the results based on the interviews can be considered high. Different questions for the interviews, different methods used for coding and analysis of the interview data, and having different researchers conducting the analysis may lead to slightly but not substantially different results.

The interview protocol was designed to answer the research questions and discussed by all authors. The interviewer was also given the freedom to ask questions outside the interview guide when the study participant seemed to be especially knowledgeable about a topic or to elaborate on previous answers. An analysis of the first interviews was used to assess if the questions asked during the interviews were able to address the research questions. The results were deemed satisfactory.

4.5 Scientific contribution

The specific contribution to the scientific body of this research is manyfold. While previous research mainly focussed on *what* impact blockchain-based technologies in supply chains can have, we developed a middle-range theory on *how* such implementations can create positive impact and detail four specific impact pathways. For example, plausibility checks can be used to catch honest mistakes as well as fraud and thus disincentivise said fraudulent behaviour. The study further advances the discussion on the role of the blockchain component in supply chain implementations and emphasises the issue of measuring impact early on. We find it concerning that only few study participants measure impact of their projects and recommend using project-specific indicators early on in order to automatically collect pertinent information that help to evaluate the success of the project.

4.6 Future research proposals

Additional research should further address the role of blockchain technology in a blockchain-enabled system and evaluate to what degree generated impacts are due to the blockchain component. In this study, we were not able with the data available to clarify to what extent the blockchain component contributes to positive social and environmental impact generated by the blockchain-enabled system as a whole. However, we believe it is important to determine the role of specific components in a system of technologies in creating impact (Köhler and Pizzol, 2020), and in particular of the blockchain component that is often used to brand, promote, and justify such system – in order to understand how to achieve the full potential of this component and to maximize its impact, or to understand what factors prevent the component to achieve its full potential. It may be impossible to isolate the effect of a single component as only the "emergent behaviour" of the system of technologies can be deemed responsible for generating impact and this systemic property does not allow disentangling the contributions of the individual components. In this case, we suggest a different approach for future research on blockchain-enabled systems, which should embrace the complexity and put more emphasis on overall system design and integration by investigating what is the importance and role of different design choices in generating positive social and environmental impact.

An important insight that we gained from this study is that there is currently a gap in measuring the impact of blockchain-enabled systems in supply chains. This gap is concerning because not measuring impact makes it difficult to evaluate the success of the implementation of blockchain. Measuring impact is not only a tool to assess the accomplishments of an implementation, but also a tool that can be used to make strategic decisions about project continuation or adaptation and can allow knowledge transfer to other projects ultimately achieving impact at larger scale. Future research could address this gap by, for example, developing a methodology to measure the impact of implementing blockchain-enabled systems and to test such methodology on real-world cases. These new measurement approaches need to be adaptable to specific use cases and allow to determine the extent to which perceived and projected impacts match actual measurable results. Since previous research on blockchain-enabled systems has mostly been conceptual, taking an experimental approach where the proposed methodology is tested in an actual project will allow to base findings on practical experiences and take into account real-world constraints that are not foreseen in conceptual studies.

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Appendices

There is one appendix for this manuscript, which is a supporting information file. It contains the interview guide (SI.1) and examples of coding for each theme (SI.2).

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Abstract

Blockchain-based technologies have emerged as a mechanism for governing sustainability in agro-food supply chain, where voluntary sustainability standards have been the main governance mechanisms over the past decades. Despite a growing body of research on blockchain-based technologies, the relationship between these two mechanisms for supply chains remains poorly understood. Therefore, this study aims at addressing this research gap and explaining their interaction. We described and assessed 16 cases of blockchain-based technologies and voluntary sustainability standards against twelve sustainability-related assessment criteria. The results show that the relationship between blockchain-based technologies and voluntary sustainability standards can be co-existing, synergistic, and antagonistic. While most cases fall under the co-existing relationship, we identified a few cases with synergistic relationships, and one case with an antagonistic relationship. We explain each type of relation and show how the system architecture and goal of a blockchain-based technology implementation are key determinants of this relationship. This study can support stakeholders in agri-food supply chain in better understanding the application of blockchain-based technologies for sustainability governance in relation to existing voluntary sustainability standards. It can further inform those stakeholders of possibilities to constructively collaborate and focus on positive social and environmental impacts within agro-food supply chains.

Keywords: supply chain governance, sustainability, voluntary sustainability standards, blockchain technology, ecolabels

Sustainability standards and blockchain in agro-food supply chains: Synergies and conflicts

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1. Introduction

Blockchain technology is a distributed ledger that is secured by a peer-to-peer network. It is virtually immutable, meaning it cannot be retrospectively changed. Over the past years, Bitcoin, the first implementation of blockchain technology and first digital system with which users could send payments directly to one another without the need of a bank (Nakamoto, 2008), has gained in popularity and inspired numerous other applications. While many applications are still within the financial sector, blockchain-based technologies (BBT) (Köhler and Pizzol, 2020) are increasingly used in other sectors as well, including applications in healthcare, art, and supply chain management.

Within supply chain management blockchain technology has been proposed as a tool to provide trusted information for consumers and increase the transparency and efficiency of the supply chains (Balzarova and Cohen, 2020; Kshetri, 2018). Supply chain management plays an especially important role in agro-food supply chains, as an effective management of these global and complex chains is key to ensure the supply of sustainable, affordable, safe, and sufficient food (Zhao et al., 2019). Particularly, within agro-food supply chains, BBT have been suggested to address social and environmental problems. Previous studies have suggested that BBT could be used to provide sustainability-related data to actors within the supply chain, third parties such as auditing bodies, and consumers (Kamilaris et al., 2019; Lim et al., 2021). This could potentially enable actors in the supply chain to address sustainability issues and consumers and upstream companies alike could make more informed purchasing decisions (Kouhizadeh and Sarkis, 2018).

BBT have also been suggested to enhance traceability across supply chains by registering every change in ownership creating a chain-of-custody (Wang et al., 2019). This, in addition to sustainability-related data such as product carbon footprints increases transparency and enables supply chain participants to market products based on production or origin characteristics (Lim et al., 2021). One example is FairChain's chocolate bar "The Other Bar". This product is promoted as contributing to "radical equality" because by purchasing it, consumers not only get the chocolate bar, but also increase equality in this particular supply chain, of which consumers see proof in the form of e.g. premiums paid to the farmers (FairChain Foundation, 2021a). BBT have further been suggested to make supply chains more efficient (Gurtu and Johny, 2019). By providing financial services for unbanked actors in the supply chain and by automating payments and other transactions BBT are expected to particularly benefit the upstream actors of agro-food supply chains, especially the farmers

(Kamilaris et al., 2019; Wang et al., 2019). Yet, research on BBTs for sustainable supply chains is still in the early stages and more investigations are needed to confirm whether the potential of BBT is truly fulfilled (Lim et al., 2021).

While the use of blockchain technology in agro-food supply chains is a recent phenomenon, the principal private governance mechanism for agro-food supply chain sustainability for at least two decades has been the adoption of Voluntary Sustainability Standards (VSS). VSS govern different aspects of sustainability (social, economic, environmental) and the commodity production process including assurance of product quality and attributes, transportation, and production and processing methods (Lambin and Thorlakson, 2018; Potts et al., 2014). Most VSS are governed by non-state actors, mainly NGOs, though some industry associations and companies have also developed their own standards (e.g. 4C; 4C, 2021). Among the more well-known VSS are Fairtrade International and Rainforest Alliance (run by NGOs), and various organic standards, usually public sector-led (EC, 2021; Fairtrade International, 2021a; Rainforest Alliance, 2021). Finally, some multi-stakeholder initiatives have developed VSS, such as the Roundtable on Responsible Soy (RTRS) and the Roundtable on Sustainable Palm Oil (RSPO) standards (RSPO, 2021; RTRS, 2021).

VSS establish a governance structure allowing producers and companies to signal specific commodity sustainability characteristics, even along disintegrated supply chains, responding to increased consumer demand for sustainability-related information about their purchases. Consequently, some VSS include certifications and eco-labels, facilitating information transfer on sustainability characteristics along the supply chain. The governance structure of VSS also specifies monitoring, usually classified as first, second and third party monitoring, defined by the relationship between the governing and the monitoring body (Lambin and Thorlakson, 2018). Generally, third party monitoring is considered more stringent and credible (Potts et al., 2014). The credibility and effectiveness of VSS is questioned by the proliferation of new standards (Lambin and Thorlakson, 2018), concerns about insufficient transparency, lack of compliance with sustainability criteria, questions about the ability to materialize desired changes (Dietz et al., 2021; Lernoud and Willer, 2017; Meemken, 2020), and limited uptake among supply chain participants (Bager and Lambin, 2020; Lernoud and Willer, 2017; Potts et al., 2014), among others.

Even though both BBT and VSS are currently used to address sustainability governance in agro-food supply chains, little is known about the interaction between these two different sustainability governance mechanisms. Investigating how VSS and BBT interact can potentially bring new valuable insights on the management of agro-food supply chains, because using BBT can potentially solve some of the issues faced by many VSS, such as insufficient transparency. BBT aim at providing easily accessible information to consumers, (e.g., scanning a QR code on the product packaging returns information stored on a blockchain on product history and characteristics) and some even have their own mechanisms to increase the sustainability of their supply chains. For example, FairChain Foundation aims at ensuring a living income for their farmers and workers. FairChain pays a premium to the farmers, similar to the Fairtrade premium, and support good agricultural practices (FairChain Foundation, 2019). Other BBT implementations rely on certifications obtained from VSS instead of developing their own. For example, Blockchain Bean sells Fairtrade International and organic certified coffee, but also includes a QR code leading to product- and program-specific information and the blockchain data can be verified by other parties (Brooklyn Roasting Company, 2021).

While there is an increasing focus on research of blockchain technology in agro-food supply chains, little is known on how BBT change governance mechanisms of agro-food supply chain sustainability and how the technology interacts with existing mechanisms such as VSS. To the best of our knowledge, the closest research to this topic is the work by Balzarova (2020) and Balzarova and Cohen (2020) discussing how the use of blockchain technology could potentially affect eco-labelling schemes. According to these scholars blockchain technology can potentially enhance the effectiveness of eco-labelling schemes by reducing negative environmental and social impacts, enhancing quality and safety standards, and increasing producer's trading power by decreasing information asymmetry (Balzarova, 2020). Balzarova also suggest that BBT could reduce some of the inefficiencies of eco-labelling schemes such as lack of data, inconsistent record-keeping, and confidentiality issues that do not allow an assessment of a program's impact (Balzarova, 2020). However, Balzarova and Cohen (2020) mention limitations to the use of blockchain technology within eco-labelling schemes. Besides technical limits that still require solving, humans interacting with the blockchain can threaten the integrity of the data. For example, while the amount of certified coffee cannot not be changed on the blockchain by downstream actors, there is still the opportunity to register a non-existent volume at the beginning and sell the certificates. Considered this seminal evidence, it is natural to raise the question of whether BBT are competing with VSS, if they are improving each other, or if they are simply co-existing.

Summing up, an analysis of the existing literature indicates the interaction between BBT and VSS remains under-investigated and seems worth pursuing to better understand how these two management systems can support, co-exist, or antagonize each other, and to anticipate the potential implication for agro food supply chain management. The objective of this study is therefore to address this research gap by analyzing the relationship between BBT and existing VSS and raising the following question: *How do blockchain-based technologies and voluntary sustainability standards interact within agro-food supply chain sustainability governance?* Since evidence shows that BBT cases have developed their own mechanisms and collaborated with existing VSS, we proceed by testing the hypothesis that the relationship between BBTs and voluntary sustainability standards can be synergistic, co-existing, or antagonistic.

The result of the study are expected to support actors and stakeholders working with VSS and BBT with a better understanding of how they affect each other, where they bring advantages to sustainability governance, and where they can learn from each other.

2. Material and Methods

This study is based on the analysis of case studies. We selected multiple existing, real-world examples of VSS and BBT implementations and performed a comparative analysis using twelve sustainability-related assessment criteria selected from a critical analysis of existing literature. Figure 1 provides an overview of the research process.

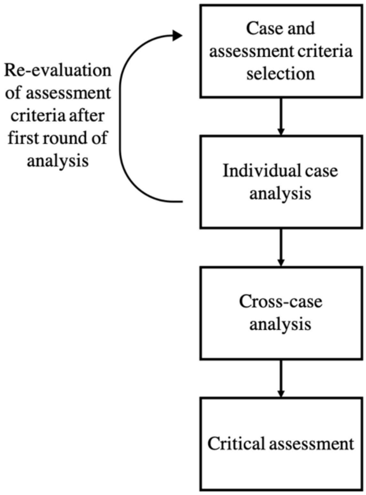

Figure 1: Research process

2.1 Selection of cases

The selection of cases was based on three pre-defined selection criteria. To be included in the analysis the case must: focus on the agro-food sector, be end-consumer facing, and address sustainability. By including selection criteria for choosing the included cases, we ensured that only cases that have a similar focus are analyzed, increasing overall comparability. To avoid including niche VSS – there are over 400 VSS across different sectors – we used data from *The State of Sustainability Markets 2020* report (ITC, 2020) to identify major VSS. After screening the VSS in the report using the selection criteria, eight VSS remained. We identify BBT cases from web-searches, blockchain-related newsletters, and the Positiveblockchain.io database (PositiveBlockchain, 2019). In total, we include eight BBT cases. Including the third selection criteria – *addressing sustainability* – meant that a specific sustainability focus was required for being considered for analysis and therefore we did not include the BBTs that only enable traceability for agro-food products. Table 1 lists the selected VSS and BBT cases.

Table 1: Overview of VSS and BBT cases considered in this study

Case	**Commodity**	**Type**	**Short description**
4C Association	Coffee	VSS	4C is an ”independent, stakeholder-driven, internationally recognized sustainability standard for the entire coffee sector” (4C, 2021).
BONSUCRO	Sugarcane	VSS	”Bonsucro is a global multi-stakeholder non-profit organisation that exists to promote sustainable sugarcane production, processing and trade around the world” (Bonsucro, 2021).
Fairtrade International	Cocoa, coffee, sugarcane, tea	VSS	”Fairtrade International is a non-profit, multi-stakeholder association [that] works to share the benefits of trade more equally – through standards, certification, producer support, programmes and advocacy” (Fairtrade International, 2021a)**.**
Organic (example EU organic standard)	All kinds of commodities incl. tea, coffee, wine	VSS	“Organic farming is an agricultural method that aims to produce food using natural substances and processes. This means that organic farming tends to have a limited environmental impact.” (EC, 2021)
ProTerra	Soybeans, sugarcane	VSS	ProTerra Foundation aims at ”promoting sustainability in the food and feed supply chain and segregated non-GMO materials” (ProTerra Foundation, 2021).
Rainforest Alliance	Cocoa, coffee, tea, bananas, oil palm	VSS	”The Rainforest Alliance is an international non-profit organization working at the intersection of business, agriculture, and forests to make responsible business the new normal” (Rainforest Alliance, 2021).
RSPO	Oil palm	VSS	“The Roundtable on Sustainable Palm Oil is a non-profit organization that […] has developed a set of environmental and social criteria which companies must comply with in order to produce certified sustainable palm oil” (RSPO, 2021).
RTRS	Soybeans	VSS	The “Roundtable on Responsible Soy Association is a non-profit organization promoting the growth of production, trade, and use of responsible soy” (RTRS, 2021).
Bext360	Coffee, palm oil	Blockchain	“Bext360 provides comprehensive and measurable accountability for critical supply chains. The SaaS platform provides unsurpassed blockchain traceability and quantifiable measurements for sustainability” (Bext360, 2021).
Blockchain Bean	Coffee	Blockchain	Blockchain Bean is a collaboration between Brooklyn Roasting Company and IBM. It aims at sourcing and serving sustainable, ethically produced coffee (IBM, 2021).

Choco4Peace	Cocoa	Blockchain	“Choco4Peace enables vulnerable Colombian farmers to improve their lives by finding markets for their cacao, allowing them to escape poverty and conflict” (Choco4Peace, 2021).
Connecting Food		Blockchain	”Connecting Food offers digital transparency solutions which create value for agri-food players and restore consumer confidence in food” (Connecting Food, 2021).
FairChain	Coffee, cocoa	Blockchain	“The FairChain Foundation’s mission is to stimulate and support business models that contribute to a truly fair distribution of wealth across all participants in the value chain” (FairChain Foundation, 2021b).
Fairfood	Coffee, coconut, tomato, cane sugar, pineapple, vanilla	Blockchain	”Fairfood accelerates the change towards a sustainable food system. [They] want everyone to benefit from truly good food, including the people at the very start of the value chains.” (Fairfood, 2021)
Farmer Connect	Coffee	Blockchain	“Farmer connect's vision is to "Humanize consumption through technology." [They] think tech should bring people together, make the world smaller, empower the individual and small business while reducing costs and inefficiencies for global enterprises” (Farmer Connect, 2021).
Provenance	All kinds of commodities incl. tomatoes, fish, and bacon	Blockchain	Provenance is “a platform and consultancy for transparency. [They] empower brands to make the sourcing and impact behind their products transparency and enable citizens to access and trust in business sustainability efforts beyond the marketing hype” (Provenance, 2021a).

2.2 Selection of assessment criteria

We used four recent publications describing the benefits of using BBT in supply chains to identify twelve sustainability-related assessment criteria for our analysis (Astill et al., 2019; Kamilaris et al., 2019; Katsikouli et al., 2021; Mahyuni et al., 2020). *Social, environmental, and economic sustainability* was mentioned as main benefits and were chosen as assessment criteria in the present study (Astill et al., 2019; Kamilaris et al., 2019; Mahyuni et al., 2020). We added *equality* to these impact-related assessment criteria to highlight how the impacts affect different players in the supply chain. *Efficiency* was chosen as another assessment criterion to cover aspects such as reduced transaction costs, digitization, automatization, and standardization, that are often highlighted in the literature (Astill et al., 2019; Katsikouli et al., 2021; Mahyuni et al., 2020). *Traceability* and *transparency* were identified as two additional assessment criteria often emphasized in the literature as main benefits of blockchain technology in supply chains (Astill et al., 2019; Kamilaris et al., 2019; Katsikouli et al., 2021; Mahyuni et al., 2020). Finally, *labelling* was chosen as an assessment criterion to cover the benefits related to consumer awareness, trust, and more informed purchasing decisions (Kamilaris et al., 2019).

A first round of case analysis was conducted with these assessment criteria (social impacts, environmental impacts, economic impacts, equality, efficiency, traceability, transparency, labelling). Based on a reflection on the results from the first analysis round, additional assessment criteria were included a posteriori: *verification, technological requirements,* *governance, process* and *outcome transparency*, to cover additional dimensions and allow for a more comprehensive analysis. The assessment criteria were then organized in three non-overlapping groups: criteria of impact, process, and communication respectively. Table 2 provides an overview of the assessment criteria used in this study. More detailed definitions of the assessment criteria can be found in the Supplementary Information.

Table 2: Overview of assessment criteria used for the analysis including a short description

Impact		**Process**		**Communication**	
Social	The impact on producers and workers, as well as their local communities.	*Efficiency*	Efficiency gains through e.g. faster information sharing, faster entry to countries, reduced costs of running the system, reduced bureaucracy, automation of processes, etc.	*Outcome transparency*	Transparency on social, environmental, and economic impacts, as well as equality and traceability.
Environmental	Reducing the impact on the environment within the supply chain.	*Verification*	How the information provided by the VSS or BBT case is verified	*Process transparency*	Transparency on how one can participate in a VSS or BBT case, what kind of criteria are important, how the criteria are changed over time, etc.
Economic	The economic impact on producers and workers. It mainly addresses how their livelihoods are ensured, but also includes access to credit and financial services.	*Traceability*	Knowing where a product has been produced, processed, etc. / visibility of product journey and included actors, chain-of-custody	*Labelling*	Product-specific information for consumers, e.g. through labels, QR codes or NFC tags, etc.
Equality	Equality between different actors in the supply chain. It relates to fairer pricing, access to markets and financial services, access to technology and information, etc.	*Technological requirements*	Level of digitization, electricity and/or cell service access, technology in place, use of technology, etc.		
		Governance	Who governs a system and who can participate in decision making processes.		

2.3 Comparative analysis of cases

We conducted the comparative analysis in three steps. Firstly, we analyzed the individual cases by qualitatively assessing each case against the assessment criteria. Secondly, we performed a cross-case comparative analysis between VSS and BBT cases. Finally, we carried out a critical assessment of the relationship between VSS and BBT cases that allowed us to characterize VSS and BBT approaches and their relationships to understand the conditions affecting them.

We started from the hypothesis that interactions between BBTs and VSS can be synergistic, antagonistic, or co-existing. A similar analytical framework was proposed by Lambin et al. (2014) to analyze potential interactions between instruments that regulate land use. This framework was useful for understanding how a combination of governance mechanisms facilitates the fulfilment of the functions required for effective governance (Lambin et al., 2014). Similiarly, the proposed framework for this study intends to support the understanding of how different implementations of BBT interact with VSS as existing supply chain sustainability governance mechanisms, and specifically which assessment criteria are central for different relationships. Synergistic interaction describes a relationship where VSS and BBT complement and reinforce each other. For instance, while existing VSS provide measures to govern sustainability in agro-food supply chains, BBT may be used to bring transparency to the measures implemented by the VSS. The antagonistic relationship describes the case when BBT and VSS oppose each other and potentially make each other worse off. This is the case when BBT and VSS compete over the same customers or the measures of one governing mechanism counteract those of the other. The co-existing relationship occurs when BBT and VSS exist side-by-side, but do not interfere with each other. This is the case when the BBT and VSS focus on different products and customers. For example, BBT may be implemented in niche markets and specialty products, while VSS may contribute to the mainstream market.

3. Results

3.1 Individual case analysis

The individual case analysis can be found in detail in the Supplementary Information. It shows for each of the 16 cases how they perform against the twelve assessment criteria. The information is illustrated in a matrix with the rows showing information on the cases and the columns providing the analysis of the assessment criteria.

3.2 Cross-case analysis

Table 3 shows an overview of the results from the cross-case analysis, summarizing for each assessment criterion the cross-cutting differences and similarities between BBTs and VSS. The results are further illustrated in the following using specific examples.

Table 3: Summary of cross-cutting differences and similarities between BBT and VSS cases identified in the cross-case analysis

Impact		**Process**		**Communication**	
Social	- VSS have their own measures such as strict requirements on no human rights abuses or access to health care (except the organic standard) - BBT either rely on measures from VSS or have their own	Efficiency	- VSS have established processes in place. Experiences from the past can lead to more efficient implementations compared to new BBT implementations. - BBT claim to be cheaper over time. BBT can connect data that was previously stored in silos and facilitate the collection of additional data. This data can be used to identify supply chain efficiencies and sustainability improvement opportunities. Automated payments and process can further lead to cost savings.	Outcome transparency	- VSS share outcomes typically online and in impact reports. They share the volumes of products certified in a given period, the amount of people impacted, etc. These are program-wide outcomes. - BBT provide batch- or even product-specific information. Blockchain Bean, FairChain, and Fairfood additionally report program-wide information.
Environmental	- VSS have their own measures such as agroforestry or limited use of pesticides - BBT either rely on measures from VSS or have their own	Verification	- VSS rely on third-party audits. - BBT may use third-party on-site audits, conduct their own, or have no on-site audits. - BBT can additionally be used to do data audits on the blockchain – if publicly accessible also by third parties and the public.	Process transparency	- VSS have clearly defined processes of how a certification can be obtained. These are regularly reviewed. About half the standards are members of the ISEAL alliance for ambitious, collaborative, and transparent sustainability systems. - BBT do not have such defined processes.
Economic	- VSS have their own measures such as premiums or trainings (except the organic standard) - BBT either rely on measures from VSS or have their own; some BBT particularly provide access to financial services, and automate payments	Traceability	- VSS have different level of traceability ranging from knowing which farm products came from (e.g. Rainforest Alliance, RSPO) to mass-balance traceability (e.g. Bonsucro). - BBT is in most cases used for providing information about the entire provenance of a product but can also improve mass-balance traceability as no certificates can be duplicated.	Labelling	- VSS in this study provide a label based on which consumers can trust that the product has been produced sustainably. - BBT include QR codes or NFC marks on products that show product-, batch- or program-specific information.
Equality	- VSS have their own measures (except the organic standard) - BBT either rely on measures from VSS or have their own. BBT further bring visibility of the supply chain to all actors and access to financial services. This can increase equality.	Technological requirements	- Levels of technological requirements for VSS vary. - BBT require the supply chain to be digitized and further rely on other technologies such as tracking devices or AI.		
		Governance	- VSS in this study have different governance models: governed by industry associations (4C), NGOs (Rainforest Alliance, Fairtrade International), public sector (organic). - BBT are privately held companies or foundations.		

Blockchain-based technologies in the supply chain that aim at having positive *social and environmental impacts* either rely on voluntary sustainability standards themselves or have their own measures similar to those found in VSS. For example, FairChain pays their farmers a premium, similar to the Fairtrade premium (FairChain Foundation, 2019). Other BBT cases such as Blockchain Bean or Provenance are certified by VSS (IBM, 2021; Provenance, 2021b). Thus, for the impact indicators, standards and project-specific measures drive positive impact. Implementing blockchain technology can, however, make more data transparently available for consumers and third parties by 1) collecting more sustainability-related data, and by 2) granting access to this data to outside parties (e.g. Connecting Food, Choco4Peace). With respect to *economic impacts*, BBT can automate payments (e.g. bext360). Blockchain technology can further be used to provide financial services to unbanked actors in the supply chain. For example, Farmer Connect farmers get a digital ID, which with they can get access to loans and keep a proof of their sales and income (Farmer Connect, 2021).

Regarding *verification*, on-site third-party audits are common practice for VSS. Such audits are not common practice for most BBT cases. It is not always clear from the material available to us if on-site audits are even conducted in BBT cases. Audits of blockchain data, such as the digitalized auditing module that provides real-time data of products by Connecting Food (Connecting Food, 2021), are interesting additions to on-site audits. Moreover, if the blockchain data is publicly accessible, outside parties such as NGOs or interested people can verify it, increasing transparency and potentially trust in the audits and programs – this can be considered as an indirect, external auditing. However, while this type of auditing may be planned by the BBT case (e.g. FairChain), no implementations of this has been observed yet.

The degree of *traceability* differs within the selected VSS and BBT cases and across the VSS cases. All BBT cases aspire to provide full traceability of the entire chain from farm to consumer. In addition to blockchain technology, this requires a variety of other technologies, such as RFID tags, and a fully digitized supply chain. Most VSS in contrast only physically separate the products from non-certified products (e.g. organic standard, 4C, RTRS), and some mainly use mass-balance traceability (e.g. Bonsucro). However, some provide a similar traceability as BBT back to the farm (e.g. Rainforest Alliance, RSPO). The method of traceability for VSS further can vary within a single standard depending on the kind of product. For example, Fairtrade International can identify the farmer for bananas that have been certified but uses mass-balance for certified oranges juice where oranges from different farms may have been mixed.

The VSSs selected for this study provide a *label* based on which consumers can trust that the product has been produced sustainably. The BBT cases included in this study put a QR code or NFC mark on the product that leads to product-, batch-, or program-specific information. The FairChain chocolate, for example, includes a QR code that allows consumers to access data on the product's journey including some impact data such as what the actors' share of the payments are – compared to traditional chocolate businesses (FairChain Foundation, 2021a).

The VSS considered in this study have different *governance* models. Some are multi-stakeholder organizations, enabling multiple stakeholders to influence standard-setting, e.g. RSPO. Stakeholder inclusion also feature in seemingly unipolar governance arrangements, where one entity governs the process. For example, Fairtrade International includes representatives of different stakeholder groups, such as members selected by producers, in their Board of Directors (Fairtrade International, 2021b). These kinds of organizations have accountability to their members and stakeholders including farmers and workers. Blockchain-based technologies in contrast are privately held companies or foundations with lower public accountability. Similarly, the *processes* for obtaining a certification for a VSS are clearly defined, transparent, and reviewed regularly. BBT cases in contrast do not have such defined processes and some of these projects (e.g. Provenance, Choco4Peace) ask interested brands to contact them to discuss possible implementation. It is unclear to outsiders if and what kind of internal rules that governs participation exist.

3.3 Critical assessment of relation between BBT and VSS

Table 4 provides an overview of characteristics of the co-existing, synergistic, and antagonistic relationships as identified in this study.

Table 4: Characteristics of the relationship between BBT and VSS cases.

Co-Existing	Synergistic	Antagonistic
- Collecting data on impacts and bringing transparency is the main mechanism BBT cases use to create impact - Access to financial services using blockchain technology is the only additional measure BBT cases add - Data on the blockchain is used to conduct audits - VSS cases are unchanged	- BBT cases implement the measures from VSS - Blockchain companies and standards collaborate. E.g. audits of the blockchain data in addition to on-site audits - VSS labels can be interacted with to get access to more product-information	- BBT cases implement their own measures – both measures using blockchain technology (e.g. access to financial services) and not using blockchain technology - Blockchain data can be accessed and audited by anyone (the public, NGOs, etc.) - VSS cases are unchanged

3.3.1 Co-existing relationship

The co-existing relationship is characterized by BBT cases that exist independently of VSS and are not big enough to be competitors. Main mechanisms to bring positive impacts to supply chains by the co-existing BBT cases are increased transparency through data collection and sharing, as well as providing access to financial services using blockchain technology. VSS are not changed by the existence of these BBT projects. The BBT projects are typically still in early stages of development and are technology-driven solutions.

Most BBT cases (four out of eight) currently *co-exist* with VSS. Farmer Connect, for example, allows farmers to obtain proof of identity and income, which in turn allows them to get loans. Consumers can further support the farmers through an app, for instance by donating to sustainability projects. When consumers buy a Farmer Connect product, they can access information about that product through scanning the QR code. While the Farmer Connect directly address the economic impact criterium and indirectly support other sustainability projects, it does not interfere with existing VSS. Similarly, VSS are not affected by these BBT cases.

3.3.2 Synergistic relationship

The synergistic relationship is characterized by a combination of BBT and VSS that improves the governance of agro-food supply chain sustainability. While VSS provide tested measures of positive impact and an established governance framework, a trusted label, multi-stakeholder governance structures, and defined processes for joining and auditing, BBTs are innovative in ensuring transparency and increasing data connectivity. The projects combine a technology-driven solution with existing sustainability governing structures.

Several of the BBT cases including Provenance, Blockchain Bean, and Fairfood are certified by existing standards. They therefore have a *synergistic* relationship with VSS. Provenance is working together with the Soil Association, a British certification body for organic standards (Provenance, 2021b). Provenance relies on the organic standard for limiting environmental impact. In the Provenance case, blockchain technology is used to create efficiencies by connecting data that was previously only available in silos. While sustainability data at different stages of the supply chain can exist, they are currently not linked. Connecting them can be used to identify gaps and ensure data consistency along the supply chain. Specifically, concerning labelling, the synergistic relationship becomes clear. While previous organic certified products simply contained a label (that consumers had to trust), the Provenance case includes an NFC-tag, a more secure alternative to QR codes, allowing consumers to access information about the product collected throughout its journey. Consumers still make purchasing decisions based on the label and additionally, if interested, can obtain information specifically about the product. The BBT projects thus complements the standard and together they improve the labelling process and increase transparency.

3.3.3 Antagonistic relationship

The *antagonistic* relationship is characterized by BBT that not only provide a technology solution (as in the co-existing relationship) but also implement their own sustainability governing mechanisms such as measures for creating positive impacts. In this situation, the BBT cases compete with existing VSS over customers. The BBT projects that have an antagonistic relationship with VSS are typically still in early stages. Their ambition and implementation do not yet fully match. The projects are a technology-driven solution combined with building new governing mechanisms for supply chain sustainability.

These BBT cases aim at building an alternative to traditional VSS. For example, FairChain Foundation claims to go "beyond certification" (FairChain Foundation, 2021c) and thereby states their intention to compete with existing VSS. FairChain implements their own mechanisms to foster sustainability. For instance, the foundation built a roasting factory in Ethiopia, a coffee exporting country, to create jobs and pays a 20% premium on top of the coffee market price to their farmers (FairChain Foundation, 2019). With the help of blockchain technology they are further testing out new mechanisms, for example, providing farmers access to financial services, such as micro-loans (FairChain Foundation, 2021a). In contrast to VSS, FairChain relies on blockchain technology for verification of sustainability claims as the technology, when implemented, will make data publicly accessible and auditable. Blockchain technology is used to provide a reliable and transparent tracking system for all transactions (FairChain Foundation, 2021c). Consumers do not find a standard's label on product, but a QR code that can be scanned to view a product's story. As a foundation, FairChain does not have the same accountability as for example a Fairtrade International standard, although some of their projects are funded by public money which comes with some accountability. Additionally, the participation process is unclear. However, FairChain does report that they are not ready to add new projects just yet but will inform interested parties if they open up for applications (FairChain Foundation, 2021d). FairChain creates a sustainability governing mechanism outside of traditional VSS, such as Fairtrade International, competes with them, and, thus, has an antagonistic relationship to those standards. VSS currently remain unchanged under this relationship type.

3. Discussion

The findings of this study show that most BBT cases co-exist with VSS, but there are cases where the two have synergistic or antagonistic relationships as well. The nature of the relationship depends on how the BBT is designed. For example, Blockchain Bean collaborates with Fairtrade and organic certified coffee in their project, incorporating the impact measures that those VSS include. FairChain, in contrast, has specifically designed a system that competes with existing VSS, as it employs its own impact measures and aims at bringing more transparency than existing governance mechanisms, with the help of blockchain technology. This emphasizes that for BBT system design – including the technology architecture, the kind of data that is collected, the potential inclusion of existing governing measures, etc. – is ultimately crucial for the kind of relationship BBT cases will have with existing VSS. System design is further important if the BBT case will bring sustainability to agro-food supply chains. Blockchain technology is only a tool. It depends on what the goal of the implementation is and how it is designed to reach this goal both in terms of the relationship BBT cases will have with existing VSS and the impact the BBT can have.

The co-existing relationship was hard to distinguish from the other two, as many of the BBT cases are still in early stages, and it is unclear if they will compete with existing VSS, eventually collaborate with them when reaching maturity and operating on a larger scale, or focus on a specialty sector and continue co-existing with VSS. This suggests that, particularly, early-stage BBT cases fall under the co-existing relationship, as they are focused on implementing their solution on a small-scale without interacting with VSS but may broaden their scope later on and redefine their relationship. Further, some BBT cases operate in niche markets or specialty segments (e.g. specialty coffee), where margins are higher, supply chains more segregated, and development more advanced. In contrast, many VSS are becoming “mainstreamed” across supply chains, moving from occupying niche markets to contributing a significant portion of the total market. If BBT cases also become mainstream, this increases the risk that relationships might become antagonistic. Additionally, it may be that cases that compete with each other over consumers leading to market or supply chain fragmentation, as too many competing sustainability governance mechanisms exist. This, in turn, could further reduce the effectiveness of all governing mechanisms, since this can make it more difficult to understand and distinguish different mechanisms.

5.1 Positive social, environmental, and economic impact

VSS have shown mixed results in terms of effectiveness. Meemken (2020) conducted a systemic review and meta-analysis on whether sustainability standards benefit smallholder farmers. While the study shows that certified farmers earn higher incomes, results are mixed and vary across standards. The question is if BBT – by themselves or in collaboration with VSS – can achieve better results and facilitate a clearer assessment of the effectiveness of the sustainability governance mechanisms employed. BBT projects can be built to specifically collect data on sustainability outcomes and impacts. For example, Choco4Peace measure socioeconomic and environmental benefits of and investment based on data registered on the blockchain (Choco4Peace, 2021). BBT can also be built in such a way that outside parties such as consumers or NGOs can audit their data and check sustainability claims on products. For this, however, the data needs to be made publicly available. A tentative hypothesis is that using BBT would allow for a better assessment of existing measures as more data is collected than in the VSS cases and available for analysis. This analysis could be carried out by the specific BBT case, but also third parties like auditing bodies or even the public. BBT could be a tool to more effectively assesses the success of specific measures in different environments. Further and long-term research is needed to investigate the effectiveness of BBT to measure impact of sustainability measures.

An assumption about the use of eco-labels and blockchain-enabled QR codes alike is that this information will allow consumers to make more informed decisions and increase purchases of sustainably produced products (Gardner et al., 2019). However, the question remains how this information needs to be designed, as simply providing more information has limited impact on changing consumer behavior (O'Rourke and Ringer, 2016). A label is easy to understand and facilitates consumer decision-making without extensive research requirements. BBT cases may lead to information overload that impedes consumer decision-making.

BBT can further improve upon existing VSS when it comes to creating economic impact. There are examples of BBT cases providing a way for farmers and workers to record their incomes and allow them to access financial services, including micro-loans and insurances (e.g. FairChain, Farmer Connect). In the future, tokens can also play an important role, as they could incentivize good behavior. For example, FairChain has been testing ideas such as providing tokens to consumers that they can either donate to plant trees or use to buy new products cheaper. Other potentially interesting ideas – that have not yet been implemented in real life – could be tracking specific behavior and tokenizing it. For example, farmers could collect tokens for producing their goods under certain circumstances – e.g. non-GMO or organically produced – and reaching a certain amount of tokens could bring benefits to the farmers. For instance, a brand could provide favorable terms for suppliers that have collected a specific minimum amount of tokens showing their positive impacts on the community or environment (e.g. tokens for implementing additional measures to reduce pesticides or protect local biodiversity). However, this may carry a risk of self-selection bias rewarding already well-off producers (at the expense of marginalized smallholders), which reduces the additional impact of implementation.

BBT are usually governed by less complex and bureaucratic structures than VSS, and this lighter governance allows them to quickly test new ideas and iterate without relying on slow approval processes. However, this also means they have less accountability to the public. This raises the question if privately held companies are better suited to innovate existing agro-food supply chains than the organizations behind VSS, as they are more flexible and independent. Studying this dynamic could be an interesting addition to the literature.

There have been media reports of VSS organizations exploring the use of blockchain technology. For example, Rainforest Alliance partnered with Nestlé and the IBM Food Trust to trace coffee (CoinDesk, 2020). According to Fairtrade International, the company is excited about the range of blockchain projects, but has not found a project that will deliver long-term value, as the projects neither consider the context of Fairtrade farmers nor offer a safety net in case their implementation fails (Fairtrade International, 2021c). This shows mixed assessments from VSSs of the potential of BBT to create positive social and environmental impact. Measuring their own impacts is therefore crucial for BBT projects.

5.2 Comparison to other studies

While most existing literature investigates VSS and BBT cases separately (DeFries et al., 2017; Kamilaris et al., 2019; Meemken, 2020; Zhao et al., 2019) and only few studies look at the link between blockchain technology and eco-labelling schemes (Balzarova, 2020; Balzarova and Cohen, 2020) – one component of the studied VSS cases – this study analysis how VSS and BBT interact with respect to governing sustainability in agro-food supply chains. We confirm that that there can be synergetic overlaps between VSS and BBT cases, particularly regarding transparency and labelling (Balzarova and Cohen 2020). Blockchain technology may further be a tool to overcome bottlenecks of insufficient data and inconsistent record-keeping of existing eco-labelling schemes that make it difficult to assess a scheme’s impact (Balzarova and Cohen 2020). We further add that accountability and bureaucracy between BBT and VSS cases vary but may be a reason for innovation. Beyond investigating synergistic interactions between BBT and VSS, we also identify cases where the relationship between the two governing mechanisms is co-existing or antagonistic showing that the range of implementations varies.

5.3 Limitations and uncertainties of the study

Limitations regarding the choice of the VSS and BBT cases deserve to be discussed. While selecting cases can be a challenge (Seawright and Gerring, 2008) – particularly regarding BBT cases that have a low level of maturity – the selected cases do represent a wide range of BBT and VSS cases in the agro-food supply chain. Selecting different cases may have led to divergent findings. Thus, the selected cases do not reflect every possible case, but instead provide insights on a wide range of cases. Additionally, there are limitations regarding the assessment. Different assessment criteria as well as different researchers may have come to diverging results. We addressed these limitations by basing the assessment criteria on literature. Four studies were consulted to identify sustainability-related criteria. The limitations regarding subjectivity was addressed by involving several researchers in the analysis process. Multiple rounds of discussion and feedback between the involved researchers took place in order to arrive at the results.

The findings of the study may hold true beyond applications in the agro-food supply chain. For example, OpenSC is a BBT case that initially implemented blockchain technology for tracking Patagonian Toothfish from bait to plate (OpenSC, 2021). Their fish are MSC certified and a synergistic relationship can be observed regarding the impact categories. The case also shows that they are able to provide more data on the legality of the fish and increase visibility of such information. Audits still take place as is the case with MSC-certified products, but additionally the data on the blockchain can be audited. Finally, consumers can scan a QR code on the product and are able to learn about the journey of the fish and see additional information such as that the vessel that caught the fish sets off their carbon footprint. However, with respect to technology requirements, governance, and process transparency, an antagonistic relationship can be identified. They require the implementation of a machine learning model, which uses data from the vessels, such as GPS data, weather, and boat speed, next to tracking technologies and blockchain technology. They too are a privately held company, and the process of becoming an OpenSC fisher or company is unclear. While this example shows that although the results of the study may be applicable outside of the agro-food sector, we cannot ensure validity for other sectors. However, some of the results can likely be transferred. For example, BBT that implement VSS will likely have a synergistic relationship. Other results may not be transferable. For example, in the automobile industry blockchain technology is employed to trace components of the battery for electric vehicles. Labelling and outcome transparency cannot be addressed in these cases in the same way as is done for agro-food products, as the battery is only one component of the entire vehicle.

Notwithstanding, it should be kept in mind that blockchain technology is still in its early stages of development. It is impossible to know how the technology will develop over time, which features will be added, which weakness will be discovered, and if it will be adopted as a governance mechanism of supply chain sustainability on a large scale or voluntary sustainability standards remain the dominant mechanism. The results of this study should be understood with this in mind.

4. Conclusions

We described in detail 16 VSS and BBT according to twelve sustainability-related assessment criteria and analyzed how the relationship between BBT and VSS can be synergistic, co-existing, and antagonistic. While most of the cases under analysis showed a co-existing relationship between BBT and VSS, we identified a few cases of synergy when a BBT cases integrate a VSS, and one case of antagonism occurring when a BBT becomes an alternative to existing VSS. We further identified specific characteristics of each relationship type. BBT cases that co-exist with VSS typically focus on making supply chain data available. Some also provide access to financial services to upstream actors in the supply chain. In cases where BBT and VSS have a synergistic relationship, VSS provide measures for positive impact, established structures, and a trusted label, while BBT increase transparency and make the existing label interactive providing access to additional product information. BBT cases that are antagonistic to existing VSS set up their own sustainability measures, make the outcome data transparent, and ultimately build an alternative to VSS.

Based on our findings a building a better understanding on how BBT and VSS interact is established. We show what advantages and drawbacks to sustainability governance in agro-food supply chains BBT can bring compared to VSS. This can inform stakeholders of the possibilities to cooperate constructively and ultimately bring positive social and environmental impacts to agro-food supply chains.

To verify that BBT and VSS can have synergistic, co-existing, and antagonist relationships requires additional long-term research with larger sample sizes and additional empirical data. Research should also confirm that the additional and more transparent data that blockchain-based technologies provide to actors within the supply chain such as brands and consumers will in fact lead to positive impacts. Furthermore, research should investigate if consumers having access to more product-specific data foster more informed decisions leading to more sustainable consumption. Finally, research should analyze if private companies are better at innovating than more bureaucratic organizations such as VSS.

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Appendices

The case study database is appended as a supplementary file.

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