Green industry through industry 4.0? Expected and observed effects of digitalisation in industry for environmental sustainability

Kumulative Dissertation

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Contents

Zusammenfassung

Die Digitalisierung der Industrie, auch „Industrie 4.0“ genannt, wird von zahlreichen Akteuren als Chance zur Reduktion der Umweltauswirkungen des industriellen Sektors betrachtet. Die wissenschaftlichen Bewertungen der Effekte der Digitalisierung der Industrie auf ökologische Nachhaltigkeit sind hingegen ambivalent. Diese kumulative Dissertation untersucht anhand von drei empirischen Studien die erwarteten und beobachteten Auswirkungen der Digitalisierung der Industrie auf ökologische Nachhaltigkeit. Ziel der Dissertation ist es, Chancen und Risiken der Digitalisierung auf verschiedenen System-Ebenen zu identifizieren und Handlungsoptionen in Politik und Industrie für eine nachhaltigere Gestaltung der Digitalisierung der Industrie abzuleiten. Ich nutze einen interdisziplinären, soziotechnischen Zugang und betrachte ausgewählte Länder des Globalen Südens (Studie 1) und das Beispiel Chinas (alle Studien). In der ersten Studie (Kapitel 2, gemeinsame Arbeit mit Marcel Matthess) untersuche ich mittels qualitativer Inhaltsanalyse Digital- und Industriestrategien aus sieben verschiedenen Ländern in Afrika und Asien auf politische Erwartungen hinsichtlich der Auswirkungen von Digitalisierung auf Nachhaltigkeit und vergleiche diese mit den erwartbaren Potenzialen der Digitalisierung für Nachhaltigkeit in den jeweiligen Länderkontexten. Die Analyse ergibt, dass die Dokumente ein breites Spektrum vager Erwartungen zum Ausdruck bringen, die sich eher auf positive indirekte Auswirkungen der Nutzung von Informations- und Kommunikationstechnologie (IKT), wie etwa auf höhere Energieeffizienz und ein verbessertes Ressourcenmanagement, und weniger auf negative direkte Auswirkungen der IKT, wie etwa auf den Stromverbrauch durch IKT, beziehen. In der zweiten Studie (Kapitel 3, gemeinsame Arbeit mit Marcel Matthess, Grischa Beier und Bing Xue) führe und analysiere ich mittels qualitativer Inhaltsanalyse Interviews mit 18 Industrie-Vertreter*innen der Elektronikindustrie aus Europa, Japan und China zu Maßnahmen der Digitalisierung in Lieferketten. Wir stellen fest, dass zwar positive Erwartungen hinsichtlich der Effekte digitaler Technologien für Nachhaltigkeit der Lieferkette bestehen, deren tatsächlicher Einsatz und *beobachtete* Effekte jedoch noch begrenzt sind. Interviewpartner*innen können nur wenige Beispiele aus den eigenen Unternehmen nennen, die zeigen, dass durch die Digitalisierung der Lieferkette bereits Nachhaltigkeitsziele verfolgt oder Nachhaltigkeits-Effekte, wie Ressourceneinsparungen, nachweisbar erzielt wurden. In der dritten Studie (Kapitel 4, gemeinsame Arbeit mit Peter Neuhäusler, Marcel Matthess und Melissa Dachrodt) führe ich eine ökonometrische Panel-Daten-Analyse durch. Ich untersuche den Zusammenhang zwischen dem Grad von Industrie 4.0 und dem Energieverbrauch sowie der Energieintensität in zehn Fertigungssektoren in China im Zeitraum zwischen 2006 und 2019. Die Ergebnisse deuten darauf hin, dass es insgesamt keinen signifikanten Zusammenhang zwischen dem Grad von Industrie 4.0 und dem Energieverbrauch bzw. der Energieintensität in Fertigungs-Sektoren in China gibt. Es können jedoch Unterschiede in Sub-Gruppen von Sektoren festgestellt werden. Ich stelle eine negative Korrelation von Industrie 4.0 und Energieintensität in hoch digitalisierten Sektoren fest, was auf einen Effizienz-steigernden Effekt von Industrie 4.0 hindeutet. Andererseits besteht eine positive Korrelation von Industrie 4.0 und Energieverbrauch für Sektoren mit niedrigem Energieverbrauch, was dadurch erklärt werden könnte, dass Digitalisierung, etwa die Automatisierung zuvor hauptsächlich arbeitsintensiver Sektoren, Energie erfordert und außerdem Wachstumseffekte hervorruft. Im Diskussionsteil (Kapitel 6) dieser Dissertation nutze ich das Ordnungsschema der drei Ebenen Makro, Meso und Mikro, sowie von direkten und indirekten Umwelteffekten für die Einordnung der empirischen Beobachtungen in Chancen und Risiken, etwa hinsichtlich der Wahrscheinlichkeit von Rebound-Effekten der Digitalisierung auf Mikro-, Meso- und Makro-Ebene. Ich verknüpfe die untersuchten Akteurs-Perspektiven (Politiker*innen, Industrievertreter*innen), statistischen Daten und zusätzliche Literatur über die System-Ebenen hinweg und berücksichtige dabei auch Gedanken der politischen Ökonomik, um Handlungsfelder für nachhaltige(re) digitalisierte Industrien abzuleiten. Die Dissertation leistet damit zwei übergeordnete Beiträge zum wissenschaftlichen und gesellschaftlichen Diskurs. Erstens erweitern meine drei empirischen Studien den begrenzten Forschungsstand an der Schnittstelle zwischen Digitalisierung in der Industrie und Nachhaltigkeit, insbesondere durch Berücksichtigung ausgewählter Länder im Globalen Süden und des Beispiels Chinas. Zweitens ermöglicht die Erforschung des Themas durch Daten und Methoden aus unterschiedlichen disziplinären Kontexten und unter Einnahme eines soziotechnischen Standpunkts, eine Analyse von (Pfad-)Abhängigkeiten und Unsicherheiten im soziotechnischen System über verschiedene System-Ebenen hinweg, die in bisherigen Studien häufig nicht ausreichend berücksichtigt wurden. Die Dissertation soll so eine wissenschaftlich und praktisch relevante Wissensbasis für eine werte-geleitete, auf Nachhaltigkeit ausgerichtete Gestaltung der Digitalisierung der Industrie schaffen.

Abstract

Digitalisation in industry – also called "Industry 4.0" – is seen by numerous actors as an opportunity to reduce the environmental impact of the industrial sector. The scientific assessments of the effects of digitalisation in industry on environmental sustainability, however, are ambivalent. This cumulative dissertation uses three empirical studies to examine the expected and observed effects of digitalisation in industry on environmental sustainability. The aim of this dissertation is to identify opportunities and risks of digitalisation at different system levels and to derive options for action in politics and industry for a more sustainable design of digitalisation in industry. I use an interdisciplinary, socio-technical approach and look at selected countries of the Global South (Study 1) and the example of China (all studies). In the first study (section 2, joint work with Marcel Matthess), I use qualitative content analysis to examine digital and industrial policies from seven different countries in Africa and Asia for expectations regarding the impact of digitalisation on sustainability and compare these with the potentials of digitalisation for sustainability in the respective country contexts. The analysis reveals that the documents express a wide range of vague expectations that relate more to positive indirect impacts of information and communication technology (ICT) use, such as improved energy efficiency and resource management, and less to negative direct impacts of ICT, such as electricity consumption through ICT. In the second study (section 3, joint work with Marcel Matthess, Grischa Beier and Bing Xue), I conduct and analyse interviews with 18 industry representatives of the electronics industry from Europe, Japan and China on digitalisation measures in supply chains using qualitative content analysis. I find that while there are positive expectations regarding the effects of digital technologies on supply chain sustainability, their actual use and observable effects are still limited. Interview partners can only provide few examples from their own companies which show that sustainability goals have already been pursued through digitalisation of the supply chain or where sustainability effects, such as resource savings, have been demonstrably achieved. In the third study (section 4, joint work with Peter Neuhäusler, Melissa Dachrodt and Marcel Matthess), I conduct an econometric panel data analysis. I examine the relationship between the degree of Industry 4.0, energy consumption and energy intensity in ten manufacturing sectors in China between 2006 and 2019. The results suggest that overall, there is no significant relationship between the degree of Industry 4.0 and energy consumption or energy intensity in manufacturing sectors in China. However, differences can be found in subgroups of sectors. I find a negative correlation of Industry 4.0 and energy intensity in highly digitalised sectors, indicating an efficiency-enhancing effect of Industry 4.0 in these sectors. On the other hand, there is a positive correlation of Industry 4.0 and energy consumption for sectors with low energy consumption, which could be explained by the fact that digitalisation, such as the automation of previously mainly labour-intensive sectors, requires energy and also induces growth effects. In the discussion section (section 6) of this dissertation, I use the classification scheme of the three levels macro, meso and micro, as well as of direct and indirect environmental effects to classify the empirical observations into opportunities and risks, for example, with regard to the probability of rebound effects of digitalisation at the three levels. I link the investigated actor perspectives (policy makers, industry representatives), statistical data and additional literature across the system levels and consider political economy aspects to suggest fields of action for more sustainable (digitalised) industries. The dissertation thus makes two overarching contributions to the academic and societal discourse. First, my three empirical studies expand the limited state of research at the interface between digitalisation in industry and sustainability, especially by considering selected countries in the Global South and the example of China. Secondly, exploring the topic through data and methods from different disciplinary contexts and taking a socio-technical point of view, enables an analysis of (path) dependencies, uncertainties, and interactions in the socio-technical system across different system levels, which have often not been sufficiently considered in previous studies. The dissertation thus aims to create a scientifically and practically relevant knowledge basis for a value-guided, sustainability-oriented design of digitalisation in industry.

Abbreviations

Full meaning	Abbreviation
Artificial Intelligence	AI
Environmental Kuznets Curve	EKC
Global Value Chain	GVC
Gross Domestic Product	GDP
Gross Value Added	GVA
Industry 4.0	I4.0
Information and Communication Technology	ICT
Information Systems	IS
International Energy Agency	IEA
International Governmental Organisation	IGO
International Panel on Climate Change	IPCC
International Telecommunications Union	ITU
Internet Of Things	IOT
Low- and Middle-Income Countries	LMIC
Non-Governmental Organisation	NGO
Purchasing Price Index	PPI
Real Value Added	RVA
Supply Chain Collaboration	SCC

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Introduction

1.1 Context

The digitalisation of industry, also referred to as "industry 4.0"[1], is changing global value creation. It therefore also has effects on the environmental impact of the industrial sector (Stock and Seliger 2016). The industrial sector accounts for approx. 25 % of global CO_2 emissions (IEA 2023), while also causing waste production, chemical use and resource depletion (Gaussin et al. 2013). Against the background of the global climate crisis and other urgent environmental problems, a transformation towards more environmentally friendly products, processes and systems, both in mature industrial systems and in emerging economies in the Global North and South is needed (Cranston and Hammond 2010; Pearson and Foxon 2012; Sachs et al. 2019). In the IEA's "Net Zero Emissions by 2050" scenario, for instance, industrial emissions are assumed to fall by approx. 25 % by 2030 – despite expected growth in industrial production (IEA 2023). This would require a decoupling (independence) of industrial production from environmental impact.

To enable this transformation of industry towards environmental sustainability, different actors across world regions expect industry 4.0 to play a key role (bitkom 2021; Bradu et al. 2022; European Commission 2022; European Digital SME Alliance 2020; George, Merrill and Schillebeeckx 2020; Mabkhot et al. 2021; Sachs et al. 2019; World Economic Forum 2017). Industry 4.0 is a key component of the European Green Deal, which aims to promote a "digital and green twin transition" towards a digitalised and sustainable economy in the EU and carbon neutrality by 2050 (European Commission 2022). Platform Industry 4.0, a German public-private initiative, proclaims industry 4.0 as an enabler of sustainability (Plattform Industrie 4.0 2019). China, as a noteworthy example of rapid industrial development in the Global South[2] in the past decades and as the largest manufacturer in the world (approx. 30 % of global manufacturing value added (UNIDO 2022)), likewise attributes high political relevance to digitalisation in industry, e.g., through initiatives such as "Made in China 2025" (State Council 2015b,c) and "Internet Plus

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[1] A more detailed definition of the term "industry 4.0" can be found in section 1.3.

[2] The term "Global South" is used in this dissertation to refer to low- and middle-income countries located in South and Latin America, Africa, Asia and Oceania, including China. In my first study, I use the term "low- and middle-income countries" which I subsequently ceased to use as I wanted to put less emphasis on the aspect of countries' income level. I am aware of controversies and historical legacies of the term "Global South" but deem these topics too wide-ranging to be discussed here. For further discussions see, for instance, Dirlik (2007), Dados (2020) and Gray and Gills (2016).

Industry" (State Council 2015a). The communicated rationale behind fostering digitalisation in industry is the expectation of more "qualitative growth" and rising incomes, while simultaneously achieving energy intensity reduction targets and "green development" (Li 2018; Li et al. 2019; Müller and Voigt 2018).

However, assessments of the impact of digitalisation in industry on environmental sustainability come to mixed conclusions. Previous scientific and private sector research has stated both positive and negative (expected) environmental effects of digitalisation (bitkom 2021; GeSI 2020; Han et al. 2016; Haseeb et al. 2019; Sadorsky 2012; Salahuddin, Alam and Ozturk 2016; Schulte, Welsch and Rexhäuser 2016; Wang and Xu 2021; Zhang and Wei 2022). There are several reasons for these inconsistent findings: first, the heterogeneity of research studies, including the scope, measurement approaches, data used, as well as geographies and historical contexts analysed, leads to variation in the assessments. Second, questions as to which *actors* develop and disseminate digital technologies under which circumstances (Lange, Pohl and Santarius 2020), and the political and corporate interests involved, including in the assessments of their effects (Freitag et al. 2021), have previously been less considered. Last, relevant systems and their interaction effects have often been neglected, for instance, between the micro and macro level, or between economic and environmental effects (Lange, Pohl and Santarius 2020; Zhang and Wei 2022). Thus, in previous literature, there is often a disconnect between the empirical, technology-centred assessment of the environmental impact of digital technologies and the social, contextual factors that determine the environmental impact, such as system level conditions or actors' intentions for digitalisation in industry.

1.2 Research questions and aim of this dissertation

Against this background, in this dissertation I aim to disentangle some contradictory expectations, and findings regarding environmental sustainability in industry by analysing expected and observed effects of digitalisation in industry with regard to environmental sustainability through three empirical studies. I link my empirical findings across levels of analysis in order to identify and discuss risks and opportunities of digitalisation in industry for environmental sustainability from a systemic, socio-technical point of view. Finally, I aim to propose recommendations to help direct digitalisation in industry towards environmental sustainability. I pose the following overarching research questions (RQs):

1. What are the expected and observed effects of digitalisation in industry with respect to environmental sustainability, considering perspectives of policy makers and industry representatives, as well as statistical evidence, in the Global North and South?
2. Linking the empirical results, which opportunities and risks arise from digitalisation in industry for environmental sustainability?
3. In light of these opportunities and risks, what are potential fields of action for promoting more environmentally sustainable (digitalised) industries in politics and industry?

These RQs will be answered through three empirical studies (RQ 1) and the subsequent synthesis of their results in the discussion section (RQ 2 and RQ 3). Table 1 gives an overview of the three empirical analyses.

Study	Title	Journal	Status	Co-authors
1	Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective (Section 2)	Environmental Science & Policy (Impact Factor: 6.4)	Published	Marcel Matthess
2	Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry (Section 3)	Resources, Conservation and Recycling (Impact Factor: 13.7)	Published	Marcel Matthess, Bing Xue and Grischa Beier
3	Industry 4.0 and energy in Chinese manufacturing sectors (Section 4)	Renewable and Sustainable Energy Reviews (Impact Factor: 16.8)	In revision	Peter Neuhäusler, Marcel Matthess, Melissa Dachrodt

Table 1: Overview of the three studies in this cumulative dissertation

The dissertation makes two main contributions. First, it contributes to the scarce literature at the nexus of digitalisation in industry and sustainability, with a focus on less investigated world regions of the Global South (first study) and on China (all studies). The case of China is examined in more detail due to China's relevance in industry and digitalisation, and its potential influence on other countries' economies and politics (see further details in section 1.4). Second, it links the emerging empirical evidence across actor groups, disciplines, countries and analytical levels to create more systemic scientific knowledge of the research field compared to previous research. I use qualitative and quantitative methods from different disciplines (qualitative content analysis, interviews, econometric panel data analysis), and analyse multiple actors' (policy makers', industry representatives') perspectives as well as panel data. In the discussion section (section 6), the results from the three empirical studies are synthesized on the micro, meso and macro level to better understand interaction effects and underlying contextual factors that determine the environmental sustainability of industry 4.0 across levels and contexts. Lastly, I identify fields of action that aim to incorporate the generated knowledge as well as political economy constraints that sustainability measures are subjected to (Mathai et al. 2021) and thereby propose practically relevant recommendations for politics and industry to steer digitalisation towards sustainability. Figure 1 summarises the research design of this dissertation.

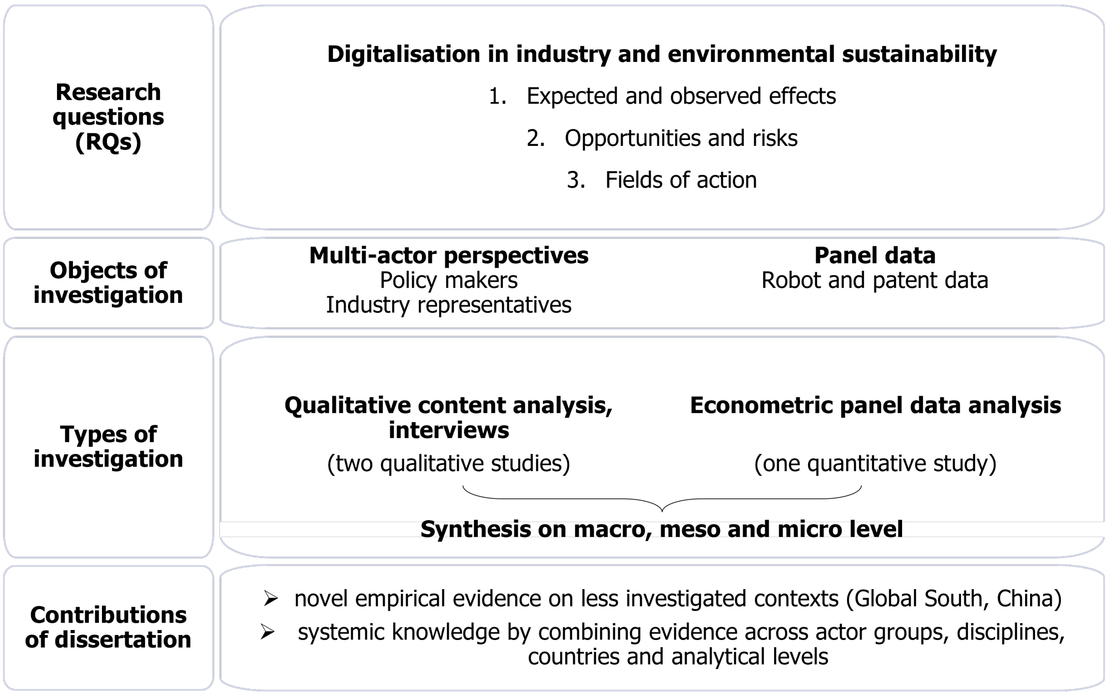

Figure 1: Overview of the research design of this dissertation

In the following sections of the introduction, I give an overview of the literature, followed by the research gaps, research assumptions, and further details on the research design of the three studies conducted.

1.3 Literature overview from an interdisciplinary perspective

This non-exhaustive literature overview serves to show the evolution of the research field of digitalisation and sustainability and to put my research into an interdisciplinary context. Over the past few decades, the relationship between environmental sustainability and digitalisation in industry has been analysed within various academic disciplines, such as informatics, business administration, economics, sociology and political science.[3] Key terms to refer to the concept of digitalisation in these scientific debates include Information Systems (IS), Information Technology (IT), telecommunication technology, Information and Communication Technology (ICT), digital technologies, smart technologies and, more recently, industry 4.0 (technologies). The distinction between the terms is not clear-cut, however, and similar topics have emerged in different disciplinary contexts.

The IS literature has provided early conceptualisations of the risks and opportunities that information systems pose to environmental sustainability within companies and industries (Chen, Boudreau and Watson 2008; Fuchs-Kittowski 2008; Melville 2010). “Green IS” refers to “the use of information systems to achieve environmental objectives” (Dedrick 2010, p. 1). For example, life cycle assessment techniques to evaluate the environmental friendliness of products and services through IT-based environmental information systems in companies have been studied (Eun et al.

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[3] I have decided to concentrate on literature mainly related to digitalisation, although the research field also builds on a long tradition of research in the sustainability sciences. I will touch upon some sustainability literature in section 1.5.

2009). Moreover, the role of IS/ICT in closing production systems has been explored, including approaches such as industrial symbiosis (Fraccascia and Yazan 2018; Grant et al. 2010; van Capelleveen, Amrit and Yazan 2018). “Green ICT”/ “Green IT” pertains to technology that has a reduced environmental impact (Dedrick 2010), but has also been used to refer to the broader environmental impact of IS (Zhang and Liang 2012).

In an attempt to systematise the effects of digital technologies on the environment, different taxonomies have been developed. Fichter (2001) and other sources in the German and European contexts (Berkhout and Hertin 2004; EITO 2002; Hilty et al. 2004; Köhler and Erdmann 2004; Kuhndt et al. 2003) have used the concepts of direct and indirect[4], as well as first-, second- and third-order effects to conceptualise the effects of ICT for society and the environment. These have been taken up in numerous subsequent studies (Hilty and Aebischer 2015; Rattle 2010; Wang, Dong and Dong 2022; Zhang and Xie 2015). Horner, Shehabi and Azevedo (2016) provide an overview of the different effect taxonomies. However, a coherent research community has not evolved yet. Numerous research communities investigate the environmental effects of digitalisation in industry from different angles, such as around the concepts of “smart manufacturing” (Abubakr et al. 2020; Ren et al. 2019), (sustainable) “innovation” (George, Merrill and Schillebeeckx 2020; Ranta, Aarikka-Stenroos and Väisänen 2021),“product/service systems” (Kjaer et al. 2019; Sakao 2013), and the “servitisation/tertiarisation of manufacturing” (Gebauer et al. 2021; Martín-Peña, Díaz-Garrido and Sánchez-López 2018; Paschou et al. 2020).

Originating in 2011 in Germany from a private-public partnership (Kagermann, Wahlster and Helbig 2013), the term “industry 4.0” has entered the academic literature in the past decade and broadly denotes the digitalisation of industry. Although there is no internationally agreed-upon definition of industry 4.0 (Culot et al. 2020), it is recognised that industry 4.0 is not only characterised by technologies but also by organisational changes in and beyond the firm (Bag et al. 2018; Beier et al. 2020c; Davies, Coole and Smith 2017; Müller, Veile and Voigt 2020; Sony and Naik 2020). Beier et al. (2020c) provide a socio-technical definition of the concept, which distinguishes between three components of industry 4.0, namely humans, technologies and manufacturing organisations. In a prototypical industry 4.0 scenario, humans collaborate (virtually) across production sites through and with (digital) technologies, based on a common reference architecture (Xu et al. 2021). Interconnected manufacturing systems rely on a set of key technologies such as sensors and artificial intelligence for real-time data collection, management, analysis, and decision-making (Martinelli, Mina and Moggi 2021). Manufacturing organisations are becoming more flexible and decentralised to accommodate changes in technologies and business models, e.g., toward more service-orientation. In effect, industry 4.0 can be seen as a holistic digitalisation concept in industry which requires far-reaching adaptation not only within the company by humans and the organisation but also by entities along the entire supply chain, to ensure the interoperability of industry 4.0 systems (Tjahjono et al. 2017).

The emergence of the concept of industry 4.0 has motivated scholars to investigate the relationship between industry 4.0 and environmental sustainability (Beier et al. 2017; Beltrami et al. 2021; Javaid et al. 2022; Kamble, Gunasekaran and Gawankar 2018; Kiel et al. 2017; Machado, Winroth and Ribeiro da Silva 2020; Patsavellas and Salonitis 2019; Stock and Seliger 2016),

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[4] Direct and indirect effects will be defined and used in the first study (section 2.2).

revisiting many topics that have been discussed under different headings (IS, IT, ICT, digital technologies, among others) in previous literature. These topics include research on Industry 4.0's impacts on environmental sustainability in firms (Garcia-Muiña et al. 2018) and supply chains (Gajšek and Sternad 2020), and its role in the implementation of holistic sustainability approaches, such as the circular economy and industrial symbiosis (Bressanelli et al. 2022; Rajput and Singh 2019; Sousa Jabbour et al. 2018; Tseng et al. 2018). However, as Beltrami et al. (2021) find in a systematic literature review on industry 4.0 and sustainability, the majority of studies are conceptual, while only 8 % test theory empirically, and only 11 % use modelling to quantitatively analyse the link between industry 4.0 and sustainability empirically.

The economics literature offers an additional relevant perspective on the topic by assessing the impacts of digital technologies on environmental indicators across various scales, e.g., energy and emissions across multiple countries and industry sectors. For instance, it has repeatedly been argued that ICT can help firms enhance (energy) efficiency in manufacturing (Bunse et al. 2011; Hilty et al. 2006; Teng et al. 2021) and that such efficiency gains would lead to effects on energy use on the aggregate level (Horner, Shehabi and Azevedo 2016; Lange, Pohl and Santarius 2020; Schulte, Welsch and Rexhäuser 2016). Furthermore, there is a scientific debate surrounding the impact of digitalisation on the decoupling and dematerialisation of the economy, as well as the substitution of traditional goods and services through digital ones, with expectations that digitalisation may result in absolute "decoupling" (independence) of economic growth from energy and resource consumption (Berkhout and Hertin 2004; Horner, Shehabi and Azevedo 2016; Rieger 2021).

As to the question of whether digitalisation impacts such decoupling differently in countries in the Global North and Global South, the Environmental Kuznets Curve (EKC) theory (Ekins 1997) has been drawn on (Nguyen, Pham and Tram 2020; Wang and Xu 2021; Zhang and Wei 2022). The EKC theory posits that environmental sustainability varies over time in accordance with a country's per capita income and stage of economic development. The EKC graph depicts an inverted U-shaped relationship between environmental degradation (y-axis) and income (x-axis). The theory implies that initially, income growth has negative environmental impacts. As socio-economic development increases, these negative impacts diminish until, after passing a threshold income (hump of the inverted U-shape) it helps to reduce environmental burden. In other words, a lower rate of use of environmental resources ("relative decoupling", "relative dematerialisation"), or even an absolute decrease in the use of environmental resources ("absolute decoupling", "absolute dematerialisation") with rising income is expected to be attained. Technological and structural change towards information-intensive industries and services in the course of shifting from agrarian to industrial and service economies is a major reason why the relationship between income and environmental degradation is hypothesised to change (Dinda 2004). Digitalisation can be considered a driver of present technological change and is thus hypothesised to proliferate an EKC relationship between growth and environmental degradation (Faisal, Tursoy and Pervaiz 2020; Han et al. 2016; Wang and Xu 2021).

The empirical assessments of the EKC regarding digitalisation, however, diverge (Wang and Xu 2021). Regarding energy and emissions, some studies see the theory affirmed, as digitalisation has been found to reduce domestic energy and emission intensity in certain economic income stages of a country under particular circumstances, up to a threshold level of digitalisation (Ahmadova et al. 2022; Hao et al. 2022; Li et al. 2022). Other studies do not support the EKC for digitalisation (Avom et al. 2020; Lange, Pohl and Santarius 2020), however, arguing that a relative energy/emissions decoupling through digitalisation will not suffice to achieve absolute decoupling of growth and exergy (useful energy). For instance, they posit that relatively energy-intensive ICT services are added to existing production instead of replacing it (Lange, Pohl and Santarius 2020; Mulder, Groot and Pfeiffer 2014). Regarding resource use, there is comparatively less empirical evidence, but several studies reject the expectation of decoupling from material use (dematerialisation) through digitalisation (Berkhout and Hertin 2004; Court and Sorrell 2020; Lawn 2001; Rieger 2021). Overall, the assessment of the validity of the EKC theory regarding digitalisation is complicated by the fact that research on digitalisation in industry is still limited at the global scale, e.g., due to a lack of indicators for industry. Often, indicators such as broadband coverage, mobile and fixed phone subscriptions are used, that may not adequately reflect digitalisation processes in the economy.

The fields of politics and sociology enrich the debate by investigating the “contestedness” and heterogeneity of the concepts of both digitalisation and sustainability, and by acknowledging the ongoing competition among actors to define their meaning and interpret their related phenomena (Büchner, Hergesell and Kallinikos 2022). Science and Technology Studies (STS), for instance, are interested in how visions of technological development shape the outcomes of innovation processes and the intersections of technical, human, and organisational systems (Kopp et al. 2019). Scholars raise critical questions as to where demands for digitalisation come from and who benefits from them, what the goals of digitalisation are and who they serve, among others (Hanafizadeh, Khosravi and Badie 2019; Palvia, Baqir and Nemati 2015). For instance, the narrative around “smart technologies” is discussed critically with respect to the concept of degrowth (March 2018). Socio-technical perspectives on digitalisation have already been present in the IS literature (Bostrom and Heinen 1977; Brooks, Wang and Sarker 2010; Melville 2010). However, the relative amount of socio-technical research at the intersection of industry 4.0 and sustainability has so far been limited (Beier et al. 2020c; Sony and Naik 2020).

1.4 Current research challenges

Following this review of the literature, several research challenges can be identified in the assessment of the effects of digitalisation in industry on environmental sustainability.

1) First, there is a scarcity of *empirical* studies on the effects of industry 4.0 on sustainability, particularly from a socio-technical point of view (Beier et al. 2020c; Beltrami et al. 2021). This is partly due to a lack of unified definitions, empirical data and established methodology for the scientific investigation of digitalisation in industry. In particular, the concept of industry 4.0 emerged relatively recently, is not well-defined (Culot et al. 2020) and its implementation is often in its early stages (depending on the firm, sector, supply chain and country) which leads to limited documentation in empirical data. Moreover, due to the interdisciplinary nature of the topic, there is no established academic community around industry 4.0, and less so around industry 4.0 and sustainability from a sociotechnical angle, which requires researchers to navigate

multiple disciplinary knowledge bases and conventions.

2) Second, there is a lack of a unified understanding of and agenda for "sustainability" in the context of digitalisation in industry, which also confounds assessments of digitalisation's effects on environmental sustainability. For instance, many studies focus on energy or emissions while digitalisation is also linked to resource depletion and water use, among other things; and trade-offs may appear between different environmental indicators (Pérez-Martínez et al. 2023). Moreover, there are also ongoing debates on the desirability of sustainability as a normative goal (of science), as well as on normativity in science altogether (as Boda and Faran (2018), discuss in detail). Where normativity is accepted as part of sustainability studies, the question remains what the appropriate level of normativity is and which norms are prioritised. Despite global agreements on the need for sustainability transformations, such as the Paris Agreement on Climate Change, the 2030 Agenda on Sustainable Development by the UN, and the European Green Deal (Linnér and Wibeck 2020), there is also opposition to and criticism of these agreements and their heterogenous normative assumptions and implications. For instance, the sustainability discourse is sometimes claimed to posit sustainability goals that are mutually incompatible (Eisenmenger et al. 2020; Spaiser et al. 2017; Swain 2018)[5], and neglect important societal perspectives, such as indigenous knowledge (Cummings et al. 2018; ICSU 2017). There are also fundamental controversies concerning the question of whether sustainability can be achieved through (eco-)efficiency gains while continuing to pursue economic growth ("green growth") or whether some variety of "degrowth" is necessary to achieve sustainability goals on a global level (Bengtsson et al. 2018; Bocken and Short 2016).

3) Third, there is a lack of research on digitalisation in industry and sustainability in the Global South, although there appear to be differences in models of industry 4.0 contingent on world regions (Bogoviz et al. 2019; Speringer and Schnelzer 2019), which in turn impact environmental sustainability. For instance, Li et al. (2022) report that robots have an energy intensity reducing effect in developed countries but not in developing countries. Existing empirical studies, however, often focus on countries in the Global North and those on the Global South face limited data availability due to lower implementation rates of industry 4.0 in regions with lower industrial and digital maturity. Cultural and language barriers additionally hinder access to existing data sources.

4) Fourth, many studies neglect the systemic interlinkages which characterise questions around the environmental impact of digitalisation in industry (Zhang and Wei 2022). Previous studies on industry 4.0 have often focused either on technological, economic, environmental or human-centred aspects and different levels of analysis (firms, sectors, economies), without considering the interplay of these aspects and levels in determining the environmental sustainability of digitalisation and its related policy recommendations (Renn, Beier and Schweizer 2021; Santarius et al. 2022; Zhang and Wei 2022). This lack of systemic thinking may also have contributed to the limited acknowledgment of potential negative effects of industry 4.0 for sustainability (Beltrami et al. 2021). For instance, the use of artificial intelligence (AI) systems is argued to improve the

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[5] For instance, the SDGs have been found to prioritise economic growth over ecological sustainability (Eisenmenger et al. 2020). SDGs 8 and 9 particularly promote (industrial) growth without a clear indication of how resource use and emissions reduction targets can be compatible with these targets.

environmental performance of firms (Frank 2021; Liu et al. 2022b), but it also leads to adaptions in human behaviour, for those using or exposed to AI systems on both the producer and consumer side (Di Vaio et al. 2020). This may influence the environmental impact of the use of AI in firms, e.g., what kinds of goods and services are being produced and how consumers will use these goods and services. Hence, there is a need to understand the co-development of digital technologies, associated beliefs, expectations, plans of usage, and behavioural changes of involved actors to determine the magnitude and direction of the (environmental) sustainability effects of digitalisation (Lange, Pohl and Santarius 2020). A systemic understanding is also particularly relevant to understand the practical feasibility (political, social, economic factors) of as well as barriers and enablers to implementing (strict enough) sustainability objectives, assuming that different actors pursue opposing agendas, face numerous path dependencies, and need to negotiate sustainability goals and measures (Miller et al. 2014; Renn, Beier and Schweizer 2021).

1.5 Research assumptions and scope of this dissertation

In view of the existing research challenges, providing a comprehensive work that encompasses a global assessment of how digitalisation in industry impacts environmental sustainability would exceed the scope of this dissertation. To develop a set of feasible research questions, I make several methodological and content-related choices and assumptions:

First, I adopt an interdisciplinary and multi-actor approach. The research is grounded mainly in economics, business administration, and sustainability science, while also incorporating ideas from the fields of political science and sociology of technology. Moreover, I consider the perspectives of multiple actors, namely policy makers and industry representatives, and additionally conduct a statistical analysis. This approach allows me to address several of the above-mentioned challenges (challenges 1, 3 and 4): 1) It helps me to overcome data scarcity and the lack of an established academic community by opening up access to various sources of data, such as policy documents, interviews and patent data. 2) It allows me to discuss systemic interlinkages between the levels of analysis. 3) Interdisciplinary approaches have been repeatedly proposed as a means to understand the trade-offs resulting from conflicting goals in sustainability transformation processes (Kaufmann and Cleveland 1995; Warburton 2003) and to find compromises at multiple levels (firms, supply chains, sectors, countries, internationally). This helps to increase the relevance of the generated knowledge for practitioners and to align societal actors towards a common environmental sustainability agenda.

Second, to navigate the fuzziness of sustainability concepts (challenge 2) and their interpretation in the context of digitalisation in industry, I limit my sustainability concept to the environmental dimension of sustainability and adopt a broad understanding of environmental sustainability goals. I mainly refer to the internationally agreed-upon objectives of the United Nations Sustainable Development Goals (SDGs) framework (UN 2023) combined with the objectives of the planetary boundaries concept (Rockström et al. 2009; Steffen et al. 2015).[6] Although

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[6] Environmental SDGs and their related planetary boundary include, first, protecting life on land (SDG 15) by not exceeding critical levels of stratospheric ozone, atmospheric aerosol landing, fresh water use, and land-system changes, and by maintaining global phosphorus and nitrogen cycles, ensuring biosphere integrity (genetic and functional diversity, including protecting biodiversity) on land and limit the introduction of novel entities. Second,

both sustainability agendas have been criticised (Bengtsson et al. 2018; Biermann and Kim 2020; Eisenmenger et al. 2020), they provide a rather comprehensive basis for the purpose of my analysis, i.e., to generate qualitative insights and conclusions as opposed to quantitative targets regarding specific environmental indicators[7]. Moreover, adopting such a broad concept of environmental sustainability allows for the flexibility to adapt my understanding of environmental sustainability to the actors and contexts of my three studies and encompass their respective environmental sustainability considerations, e.g., firms' supply chains' environmental performance (study 2) as opposed to manufacturing sector-level performance (study 3). Regarding the debate about normativity in science, I consider making normative assumptions in sustainability science as justified, since research on sustainability is "problem-driven", as opposed to being concerned mainly with the advancement of knowledge in a specific discipline (Clark 2007).[8]

Third, to address the lack of research on the effects of industry 4.0 on environmental sustainability in the Global South (challenge 3), I first analyse policy expectations of several countries in Africa and Asia to give a broad account of countries across the Global South, and subsequently focus on the example of China. The focus on China is motivated by several factors: 1) As the largest energy consumer and manufacturer in the world (21 % of world total final energy consumption in 2019 (IEA 2021b) and 30.5 % of global manufacturing value added in 2021 (UNIDO 2022)), China plays a crucial role in reducing the environmental footprint of industries. 2) The implementation of industry 4.0 in China is more advanced than in other emerging economies (Lambrechts, Sinha and Marwala 2021), which leads to greater data availability for a scientific investigation of the effects of industry 4.0. 3) Through its soft power, expansive policy and importance as a trading partner, China affects digital development in other countries in both the Global South (Gong 2019; Shubo Li and Helge Rønning 2013) and Global North – and presumably its (un-)sustainability as well. China is the EU's largest partner for imports (20 % of total imports to the EU), with the two largest groups of imported goods being telecommunications equipment and automatic data processing machines (Eurostat 2023). Technology influx from China through trade thus (indirectly) influences energy and resource efficiency of digitalisation in the countries where those technologies are used. It has further been argued that China aims to extend its influence on (digital) development through the expansion of operation of Chinese technology companies, which are said to collaborate closely with the state authorities (pursuing "digital neocolonialism", as stated by Gravett (2020)). Thus, digitalisation in Chinese industry is likely to have a considerable impact on global industry and digitalisation, as well as its environmental sustainability.

Fourth, to link interdisciplinary insights and discuss systemic interlinkages (challenges 1 and

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they include protecting life underwater (SDG 14) by ensuring biosphere integrity of ocean systems (including protecting ocean biodiversity) and limiting ocean acidification. Third, they include fostering climate action (SDG 13) to limit climate change to well below 2 degrees Celsius, as agreed upon in the Paris Agreement (Schleussner et al. 2016; Steffen et al. 2015; UN 2023). While "sustainable production and consumption" (SDG 12) does not mainly concern ecological indicators, its targets include sustainable management of resources and reduction of waste.

[7] It should be noted that there are generally still questions around the attribution of SDGs and planetary boundaries to the national and sub-national level (Häyhä et al. 2016; Li et al. 2021). Recent research, for instance, aims to quantify specific material and energy reduction targets broken down by industry sector (Hjalsted et al. 2021).

[8] Moreover, as Boda and Faran (2018) poignantly note: Without the (perceived) need and normative goal of reducing environmental burden, there would be no need to pursue environmental sustainability science.

4) I adopt a socio-technical understanding of digitalisation as an analytical lens in this dissertation. I view digitalisation in industry not mainly as a technical but as a social, organisational and structural (political, economic, etc.) phenomenon on multiple levels (Beier et al. 2020c; Kopp et al. 2019; Seidel, Recker and vom Brocke 2013; Sony and Naik 2020; Trevisan et al. 2023). This implies that there is a mutual dependence between the humans that form organisations, the organisations, the technologies, and the structures within which all three are embedded. For instance, organisations and political structures (such as public funding schemes) affect people's preferences and choices regarding technology development and use (see, e.g., Keller (1972), Orlikowski (2000), Shani et al. (1992)). The use of technologies, in turn, creates path dependencies to which organisations and humans adapt. The mutual dependence of these entities interacts with the environmental sustainability of the socio-technical system. A socio-technical approach thus also implies that there are no unidirectional, causal relationships between technologies and environmental effects and that studies at this intersection are faced with multilayered complex mechanisms (Renn, Beier and Schweizer 2021). A simplified socio-technical framework adapted to my dissertation's context is illustrated in Figure 2.

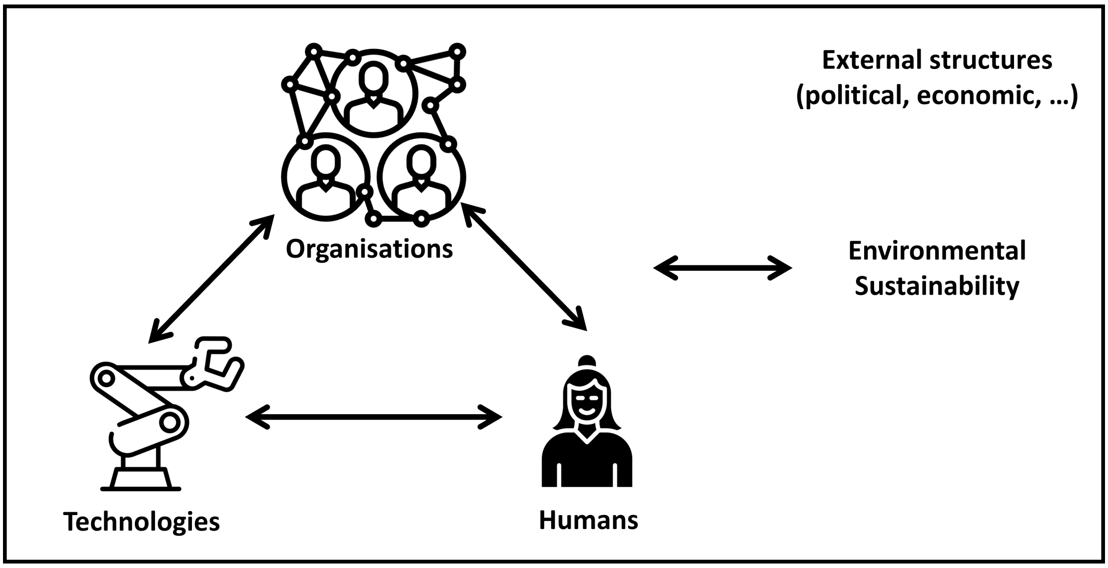

Figure 2: Socio-technical system approach to industry 4.0 and sustainability: Technologies, organisations, humans, the surrounding structures and the environmental sustainability of the socio-technical system are interdependent. Own elaboration based on Melville (2010) and Beier et al. (2020c); Icons from Flaticon (undated[a]).

Based on my socio-technical understanding of digitalisation in industry, I adopt different definitions of digitalisation ("digital transformation", "use of information and communication technologies (ICT)", "industry 4.0") depending on the individual contexts and foci of my three studies. For instance, analysing countries of the Global South in the first study, I consider a wider range of digital technologies in order to accommodate countries' heterogeneity, whereas in the third study in the context of China, I adopt a definition of industry 4.0 characterised by eight core technologies. Since my dissertation aims to explore socio-technical, rather than purely technological aspects of digitalisation, varying definitions allow for more flexibility in incorporating different knowledge bases and languages used in political or private-sector contexts, and in interpreting the studies' results in their entirety in the discussion section.

By making the aforementioned choices, certain pertinent topics will not be covered in this dissertation. I do not explore the technology frontier and analyse hardware's or software's technical potential to optimise environmental performance of industrial production (e.g., the technical implementation of data collection and analysis along the supply chain). I also do not aim to provide quantitative assessments of environmental impacts of digital technologies on the product, process and system levels in industry. For instance, I do not conduct life cycle analyses regarding the environmental effects (energy and material consumption, emissions, etc.) of digital technologies in industry. While such assessments are insightful, they answer technological rather than socio-technical research questions. As previous studies have found a lack of systemic thinking to be a major challenge for the scientific and societal understanding of digitalisation's environmental effects (Santarius et al. 2022; Zhang and Wei 2022), however, I deem a mainly qualitative assessment of the interlinkages between actors' expectations and (quantitative) empirical effects of digitalisation across the analysed contexts to be an appropriate and fruitful approach to further this understanding.

Furthermore, as described above, I limit my assessment to the environmental dimension of sustainability, although sustainability is viewed as a holistic concept in the SDG framework, which aligns human-centred and environmental values. However, for the purposes of this dissertation, I appeal to the argument that the biosphere forms the foundation for human well-being and that environment-centred SDG can be prioritised over other SDG (Folke et al. 2016). This notwithstanding, I acknowledge that there are social and economic trade-offs and obstacles to implementation of more sustainable pathways with regard to digitalisation in industry. For example, given large differences in economic prosperity between the Global North and Global South, (previously) deprived actors criticise the injustice which could be caused by sustainability transformations, mainly focusing on limiting (individuals' and countries') access to resource use and rights to pollute (Adams 2008; Hayward 2007). The same may apply to the question of how digital technologies are used in industry to either foster income growth or reduce industrial environmental impact. By applying interdisciplinary methods and considering the perspectives of various actors, as well as perspectives from the Global North and Global South in this dissertation, I aim to consider the trade-offs between socio-economic and environmental sustainability goals in industry, and discuss implications of these trade-offs throughout the three empirical studies and particularly in the discussion section (see, e.g., section 6.1.3).

In the limitations section (section 6.3) of this dissertation, I discuss further limitations that arise from my design choices, and subsequently suggest avenues for future research (section 6.4) to address the shortcomings of this dissertation.

1.6 Research design

Based on this theoretical foundation and defined scope, I aim to address the overarching RQs through three empirical studies that I conducted and submitted to or published in peer-reviewed scientific journals between 2019 and 2023. Table 2 provides an overview of the three studies.

Title	**Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective**	**Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry**	**Energy use in Chinese manufacturing sectors**
Section	Section 2 (Study 1)	Section 3 (Study 2)	Section 4 (Study 3)
Analysed contexts	Policy makers' expectations as stated in national policies	Industry representatives (supply chain experts') expectations	Statistically observed links between digitalisation and energy in manufacturing sectors
Data and methods	Qualitative content analysis of digital and industrial policy documents across seven countries in Africa and Asia	Expert interviews in international and Chinese firms from the electronics industry	Econometric analysis of patent data, robot data, and energy use in Chinese manufacturing sectors
Type of investigation	Qualitative (actor perspective)	Qualitative (actor perspective)	Quantitative (statistical analysis)
Research gap	Few empirical studies on the environmental effects of digital transformation in industry in low- and middle-income countries, and policy expectations regarding these effects are not well understood	Few empirical studies on Industry 4.0 in supply chains which focus on its role in collaboration between supply chain partners in the Global North and Global South and its role in environmental upgrading along the value chain	Few studies on the heterogeneity of digital technologies' impact between manufacturing sectors; mainly general digitalisation indicators, such as broadband, mobile internet access or ICT investments are used, so the impact of recent industry 4.0 developments is not well understood
Research question	What are developing countries' policy makers' expectations about the role of information and communication technologies in industry for environmental sustainability?	How are digital technologies currently used in supply chain collaboration (SCC) and what are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?	How far is the degree of I4.0 linked to energy consumption and intensity in industry sectors?
Main disciplinary influence	Political science, sociology of technology	Business administration, (development) economics	Economics

Table 2: Summary of the research designs of the three studies

The individual studies inform the overarching RQs (see section 1.2) as follows: In sum, the three articles answer the first overarching RQ. The second overarching RQ will be answered by systematising and linking the empirical results of the three studies on the macro, meso and micro level. The third overarching RQ will be answered by taking a more practice-oriented perspective appealing to transdisciplinary research approaches (Renn 2021), consulting additional (non-scientific) literature, discussing interactions between the levels of analysis and incorporating political-economy perspectives (Mathai et al. 2021). On this basis, practical fields of action will be proposed.

The following sections 2, 3 and 4 comprise the three empirical studies of my dissertation. Section 5 provides a summary of each of the three studies and their individual contributions. Section 6 presents the discussion, limitations, and future research possibilities. Section 7 provides the conclusion. This is followed by the appendix, including contributions to conferences, a publication list, an extended German summary, additional administrative information, and the references.

2

Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective

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Abstract

With the increasing use of information and communication technologies (ICTs) in industrial production, the risks and opportunities of these technologies for environmental sustainability as well as political awareness about these risks and opportunities become increasingly important. In this paper we analysed digital and industrial policies of 4 Sub-Saharan African countries (South Africa, Rwanda, Kenya, Nigeria) and 3 East Asian and Pacific countries (China, Thailand, Philippines) regarding their expectations about the impacts of ICTs in industry for environmental sustainability. We built on existing frameworks for the assessment of ICTs that distinguish between direct environmental effects which occur during the lifecycle of ICTs and indirect environmental effects which result from the application of ICTs in a variety of production processes and economic activities. We used qualitative content analysis to explore and analyse policy expectations regarding both direct and indirect environmental impacts of ICTs in industry. Our analysis showed that policies express a broad range of vague expectations focusing more on positive indirect impacts of the use of ICTs, e.g. for enhanced energy efficiency and resource management, than on negative direct impacts of ICTs, e.g. electricity consumption of ICTs. Moreover, expectations differed greatly between countries and there was no shared theme that emerged in all policies. We suggest that policies must go beyond awareness of selected opportunities towards the integration of a more systemic understanding of interlinked direct and indirect impacts and pursue targeted measures to make

ICTs tools for environmentally sustainable industries.

Keywords

Digitalization, Sustainable industrial development in low and middle income countries, Industry 4.0, Computerization, Digital and industrial policy, Information and communication technologies

Highlights

- Policies include expectations of direct and indirect environmental effects of ICTs in industry.
- Positive expectations are, for instance, increased resource and energy efficiency.
- Negative expectations exist, for instance, regarding electronic waste disposal.
- Expectations differ between the analysed countries' policies.
- Policies barely recognise links between risks and opportunities that ICTs pose for environmental sustainability.

2.1 Introduction

Industrial production has significant environmental implications worldwide. The industrial sector accounted for 36 % of global total final energy consumption and 24 % of global CO2 emissions in 2014 (IEA 2017b). While energy efficiency of production is improving in many areas, the overall environmental burden presented by industrial production is assumed to grow (UNIDO 2017b). With accelerating digital transformation in industry, i.e. the increasing development and application of information and communication technologies (ICTs) in manufacturing and service industries (IEA 2017a; WBGU 2019a), science and society discuss the role of ICTs for environmentally sustainable industrial development (Banga and Velde 2018; GeSI 2015; World Bank 2016).

A broad body of scientific literature on the implications of the digital transformation for economy, society and the environment has emerged since the 1990s (Berkhout and Hertin 2001; Broadband Commission 2013; ITU 2018a; Mansell and Wehn 1998), although less so for environmental sustainability implications of ICTs in developing countries (Heeks 2014). Empirical evidence regarding the environmental risks and opportunities of the digital transformation is mixed and often points to uncertainties regarding the net environmental effects of the digital transformation (Beier et al. 2020a). Despite these uncertainties, a widening range of purposes and goals have been ascribed to the digital transformation in industry, varying across national policies. Although still scarce, policy analyses have shown that numerous political endeavours of low- and middle-income countries (LMIC)[9] revolve around the idea of ICTs leading to socio-economic development and economic growth (Friederici, Ojanperä and Graham 2017). For instance, the relevance of the digital transformation in embedding local industrial production in global value chains is being discussed (Africa Growth Initiative 2018). With regard to the relationship between environmental sustainability and ICTs, Fritzsche, Niehoff and Beier (2018) find that there is an emerging discourse of intergovernmental organisations (IGOs) on the role of ICTs for environmentally sustainable industrial production. Notably, they hold that research has yet to investigate how national institutions address this topic (Fritzsche, Niehoff and Beier 2018).

Against this backdrop, we pose the following research question: What are developing countries' policy makers' expectations about the role of ICTs in industry for environmental sustainability? Using qualitative content analysis, we analyse expectations regarding the role of ICTs in industry for environmental sustainability in national industrial and digital policies of four Sub-Saharan African countries (South Africa, Kenya, Rwanda, Nigeria) and three East Asian and Pacific countries (China, Thailand, Philippines). We develop a framework to categorise the expectations regarding environmental effects of ICTs which we found in the analysed policy documents. We highlight five examples of these expectations, discussing in the respective country contexts the envisioned goals that are portrayed in the policies.

The aim of this paper is to deepen our understanding of how policy makers in LMIC portray the relationship between ICTs, industrial development and environmental sustainability. This is important for various reasons: Firstly, policies play an important part in shaping industrial and technological development (Palvia, Baqir and Nemati 2015) and there are often gaps between

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[9] We use the term “low- and middle-income countries” interchangeably with the term “developing countries”.

the design of the use of ICTs within policies and actual conditions on the ground (McBride and Stahl 2010). Analysing policy makers' expectations can help to bridge the gap between currently isolated debates of technology-centred research on the one hand and policy making on the other hand (Fritzsche, Niehoff and Beier 2018). Secondly, policy analysis may serve as an early warning system for path dependencies related to the proliferation of ICTs. For instance, it may unveil technologies as carriers of shifting political and corporate interests in evolving socio-technical systems (Cordella and Iannacci 2010). Thirdly, policy analysis can reveal specific sustainability challenges of policy makers in LMIC. With digital and industrial policy making still at an early stage, LMIC policy makers face the challenge of simultaneously balancing growth of incomes, environmental and social concerns in order to deliver win-win-win solutions (UNIDO 2017a). Analysing how far these goals are already reflected in policies might give impulses at the intersection of policy-making for sustainable digital and industrial development.

2.2 Framework: environmental effects of ICTs in industry

For our application in the industrial context we adapted existing frameworks by Beier, Niehoff and Xue (2018), Berkhout and Hertin (2001) and Erdmann et al. (2004) which categorise the environmental effects of ICTs. As further elaborated in the methodology section, the framework is used in our content analysis as an analytical lens to structure and interpret policy expectations.

We broadly distinguished between the main categories of direct environmental effects and indirect environmental effects of ICTs. Direct environmental effects are impacts associated with the lifecycle of ICTs (Berkhout and Hertin 2001). Indirect environmental effects result from the application of ICTs in other goods and services. Although earlier studies have already investigated potential indirect environmental effects of ICTs in different contexts (Erdmann et al. 2004), we deemed it necessary to account for rapid technological advancements in recent years and consider the corresponding scientific insights regarding their impacts. Moreover, we regarded the application of a framework with an emphasis on the industrial context as particularly fitting for our analysis.

Within the category of indirect effects, Beier, Niehoff and Xue (2018) highlight three subcategories where the application of ICTs in industry can be linked to environmental risks and opportunities: resource efficiency, sustainable energy and transparency. Furthermore, we subsume systemic effects of the use of ICTs, e.g. rebound effects (Erdmann et al. 2004), under the main category of indirect effects. The effect categories are summarised in Figure 3.

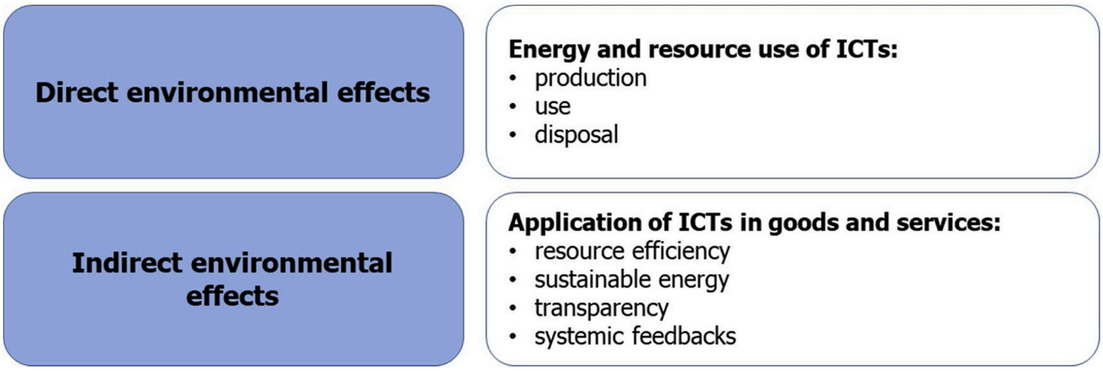

Figure 3: Effect categories of environmental effects of ICTs in industry, adapted from Beier, Niehoff and Xue (2018), Berkhout and Hertin (2001) and Erdmann et al. (2004).

In the results section, we illustrate the two suggested effect categories with five examples. These examples emerged as particularly noteworthy and suitable for further analysis from the content analysis because a) a tangible issue related to ICTs (e.g. e-waste, energy) was expected to be b) targeted by a specific solution (e.g. regulation). The examples are summarised in Table 3.

Effect category	No.	Example	Focus country
Direct environmental effects	1	E-waste and legal frame	Kenya, Nigeria and Rwanda
	2	Green ICT	Thailand, Philippines, Nigeria and Rwanda
Indirect environmental effects	3	3D print in the Aerospace industry	South Africa
	4	Renewable energy proliferation	Rwanda, Kenya and China
	5	Digital monitoring of resource use	China

Table 3: Examples of policy expectations and their corresponding effect categories.

2.2.1 Direct environmental effects of ICTs

Direct environmental effects are impacts of resource and energy use along the lifecycle of ICTs, i.e. production, use and disposal of ICTs. With respect to resource use in production, ICTs for large-scale use in industry will require increasing amounts of materials in their production. A study commissioned by the German Resource Agency, for instance, expects the demand for critical materials, such as lithium, dysprosium/terbium and rhenium, used for emerging technologies, many of which are related to the use of ICTs in industry, to exceed production of these materials (2013 levels) two times by 2035 (Marscheider-Weidemann et al. 2016).

With respect to energy use of ICTs, while electronic components like sensors and controllers become smaller and more energy-efficient, the number of digital components increases in a digitalised industry. Moreover, the underlying infrastructure (such as data centres, servers, networking gear, power and cooling equipment) requires a growing amount of electricity. In a study on the estimated use-stage electricity demand by 2030, Andrae and Edler (2015) find that ICTs might, in the worst case scenario, use up to 51 % of global electricity and be responsible for 23 % of global greenhouse gas emissions.

With respect to the disposal of ICTs, e-waste accumulation is an increasingly important issue, particularly in low- and middle-income countries. While global annual e-waste was estimated to stand at 45 million tonnes in 2016, a projected 52 million tonnes will be generated in 2021 (Baldé et al. 2017).[10] Although 95 % of the useful materials from a computer could potentially be recycled (Robinson 2009), the decreasing size of devices makes it more difficult to recycle rare materials (Hilty 2011). In 2016, 80 % (35,8 Mt) of global e-waste was not recycled, 4 % were disposed as residual waste, whilst the remaining 76 % remained untracked (Baldé et al. 2017). Most of the untracked e-waste is exported from high to low- and middle-income countries and disposed in landfills, or else burned and dissolved in acids (Heeks, Subramanian and Jones 2015; Nnorom and Osibanjo 2008; Robinson 2009).

2.2.2 Indirect environmental effects of ICTs

Indirect environmental effects result from the application of ICTs in other goods and services, e.g. digital data unveiling resource waste or recycling potential in a production process. With respect to resource efficiency in industrial production, ICTs have been discussed as enablers to reduce resource use in different contexts (Gu et al. 2013; Jayal et al. 2010; Song et al. 2018), for instance through additive manufacturing. Additive manufacturing (AM) enables the creation of three-dimensional objects, applying material layer-by-layer on the basis of a digital plan of the object (Gebler, Schoot Uiterkamp and Visser 2014). AM has the potential to improve resource efficiency and enable lifecycle management (Ford and Despeisse 2016). The use of “Recycle Bots” to recycle polyethylene for the production of 3-D printing filament, for instance, has been shown to result in a reduction of recycling-related energy consumption of up to 70 % (Kreiger et al. 2014). Gebler, Schoot Uiterkamp and Visser (2014) see a potential of reduced CO2 emissions through AM considering the emission-in-tensity per unit of output. However, Birkel et al. (2019) point to the danger of increasing waste production. High customisation might lead to difficulties in reducing, reusing, recycling and reselling products.

With respect to transparency, more granular and real-time data are important requisites for more sustainable industrial production processes (Beier, Niehoff and Xue 2018). The environmental impacts of products and services occur at different points along the life cycle in different geographical locations. Increasing transparency by collecting and consolidating data from geographically dispersed value chains gathered at all stages of the product (and service) life cycle can enhance sustainability management within and across firms. For instance, real-time data flows from machine-to-machine communication and electronic product tags could facilitate the implementation of the “circular economy” concept with the aim of creating vertically integrated and cross-industry networks with closed material loops (De Sousa Jabbour et al. 2018; Tseng et al. 2018).

With respect to sustainable energy, some studies argue that the use of ICTs opens possibilities for integrating renewable energy into the energy mix for industrial production, for instance

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[10] While not all e-waste is generated by ICT devices (also refrigerators, TVs, etc.) the contribution of ICT devices to e-waste is fuelled by increasing numbers of, among others, mobile devices (GSMA 2017).

through smart grids (Amin and Wollenberg 2005). On the supply side, consumers can be integrated in the provision of electricity by photovoltaic (PV) panels, making them “prosumers“ (Grijalva and Tariq 2011). On the demand side, fluctuating renewable energy flows could be matched more easily with flexible industrial production scheduling and industrial orchestration, i.e. the process of optimised energy production and use through more granular data and simulation methods to control manufacturing processes in accordance with energy availability (Beier, Niehoff and Xue 2018; Ding, Jiang and Zheng 2017; Weinert, Chiotellis and Seliger 2011). For example, virtual power plants can help to visualise and manage the energy capacities fed into and taken from the grid by various energy sources and energy consumers (Pudjianto, Ramsay and Strbac 2007).

Additionally, ICTs have systemic effects on production and consumption patterns, as well as individual behaviour, attitudes, values, and governance processes. Firstly, ICTs are assumed to increase productivity and thus accelerate economic growth (Farhadi, Ismail and Fooladi 2012). Empirical studies come to varying results about the extent of the productivity effect (Hawash and Lang 2019; Pieri, Vecchi and Venturini 2018). Secondly, ICTs have been discussed in the context of achieving the decoupling of economic growth from resource or energy use through efficiency increases, and to arrive at a less material intensive economy (Berkhout and Hertin 2004; Erdmann et al. 2004; Hilty 2008). Increases in (energy) efficiency, however, tend to be counteracted by systemic feedback effects, also called “rebound effects“: If the ICT-related economic growth rate in an industrial sector exceeds the increase in energy or material efficiency enabled by ICTs in this sector (decoupling rate), efficiency gains through ICTs are overcompensated and total resource use increases (Hilty, Lohmann and Huang 2011; Polimeni et al. 2015; Pothen and Schymura 2015). However, in a simulation study of how energy demand would develop without ICT-driven energy efficiency improvements, the authors argue that efficiency gains induced by ICTs compared to a scenario without ICTs can lead to decreases in energy use in some domains such as in the freight transport sector (Achachlouei and Hilty 2015).

2.3 Methodology

2.3.1 Country and policy document selection

Given our interest in the digital transformation in industry and its relation to environmental sustainability, we assumed that digital and industrial policy documents would yield relevant policy expectations. Consequently, we scanned the websites of authorities on the highest administrative level for these documents in our focussed regions, Sub-Saharan Africa and East Asia and Pacific. We excluded informal reports such as blogs, surveys, or workshop reports. Moreover, we excluded publications with too narrow thematic scopes regarding our research question, such as cybersecurity strategies. Our specific search terms are summarised in Table 4.

	Digital policy	**Industrial policy**
Search terms	digitalisation strategy, ICT development plan, ICT policy, ICT strategy, digital strategy, digital policy, digitalisation policy/strategy and economic development policy	digitalisation strategy, ICT development plan, ICT policy, ICT strategy, digital strategy, digital policy, digitalisation policy/strategy and economic development policy

Table 4: Search terms for policy documents

We screened the remaining policies from 27 countries, a total of 38 policies, to gather preliminary insights regarding the degree to which these documents provide information relevant to our research question. We discarded documents that did not include passages and chapters on the environmental effects of ICTs in industry. Consequently, 25 policies from 21 countries were discarded. A list of excluded documents is provided in Appendix A. The remaining 13 policies from seven countries fell under the scope of our research topic and were thus selected for the qualitative content analysis. These documents were not restricted to single topics, but instead covered the cross-cutting issues of digital transformation, industrial development and environmental sustainability that we aim to investigate. The country selection process is summarised in Figure 4. A list of the selected documents can be found in Table 5.

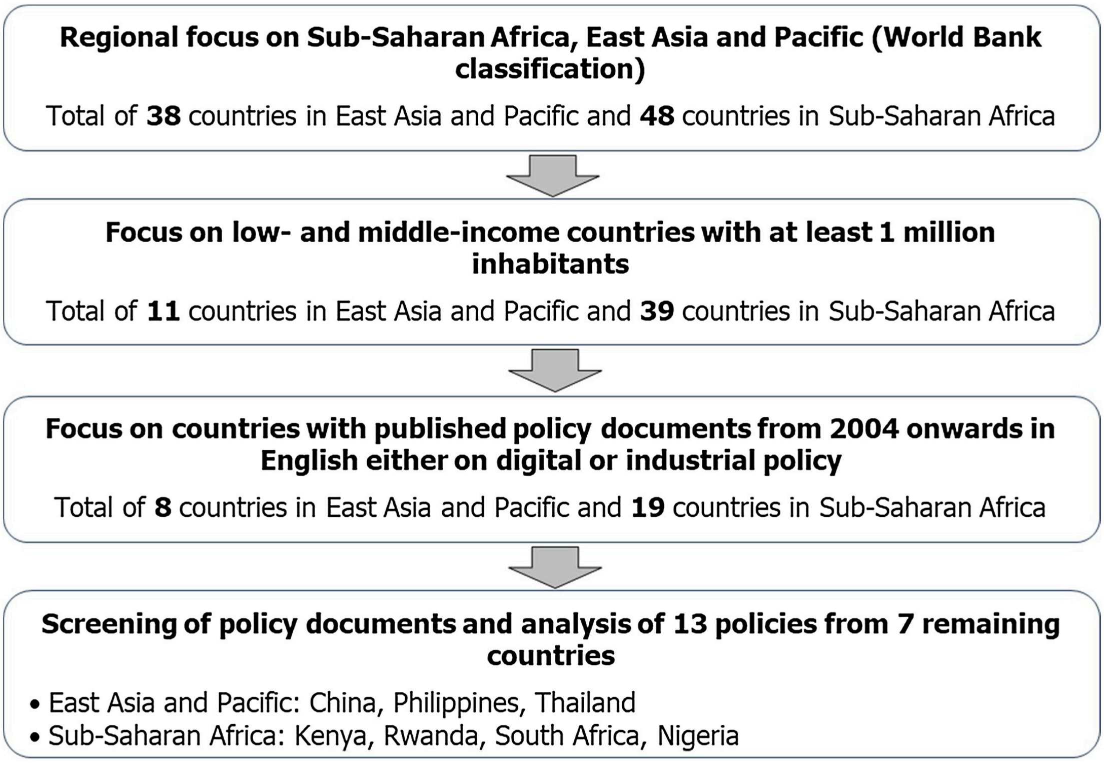


Figure 4: Document selection process

No.	Country	Name of the document	Type of document	Year of publication	Author
1	China	State Council's guidance on actively promoting Internet + action	Digital policy	2015	State Council of the People's Republic of China
2	China	Made in China 2025	Industrial policy	2015	State Council of the People's Republic of China
3	Philippines	The Philippine Digital Strategy Transformation 2.0: Digitally empowered Nation	Digital policy	2014	Commission on Information and Communications Technology
4	Thailand	Executive Summary Thailand Information and Communication Technology Policy Framework (2011-2020) ICT2020	Digital policy	2010	National Electronics and Computer Technology Center
5	Thailand	The twelfth national economic and social development plan (2017-2021)	Industrial policy	2016	Office of the National Economic and Social Development Board
6	South Africa	Industrial Policy Action Plan 2018/19 – 2020/21	Industrial policy	2018	Department of Trade and Industry
7	South Africa	National Integrated ICT Policy White Paper	Digital policy	2016	Department of Telecommunications and Postal Services
8	South Africa	National e-Strategy. Digital Society South Africa	Digital policy	2017	Department of Telecommunications and Postal Services
9	Kenya	National ICT Masterplan 2014-2017	Digital policy	2014	Ministry of Information Communications and Technology
10	Kenya	National Information & Communications Technology Policy	Digital policy	2016	Ministry of Information Communications and Technology
11	Kenya	Industrial Transformation Programme	Industrial policy	2015	Ministry of industrialization and enterprise development
12	Nigeria	National ICT Policy	Digital policy	2012	Ministry of Communication Technology
13	Nigeria	Smart Rwanda Masterplan 2015-2020	Digital policy	2015	Ministry of Youth and ICT

Table 5: Selected policy documents

2.3.2 Qualitative content analysis

For the analysis of the policy documents, we chose qualitative content analysis (Schreier 2015). The goal of qualitative content analysis is to get a condensed description of a phenomenon, building on a set of categories to describe it (Elo and Kyngäs 2008), which in our case are the policy expectations regarding the environmental effects of ICTs in industry. We used the software MAXQDA to conduct the qualitative content analysis. In the first step, we read the selected policy documents in detail and identified general themes and subthemes. We assigned an initial category to each new aspect relevant to our research question, for instance, the category "renewable energy".

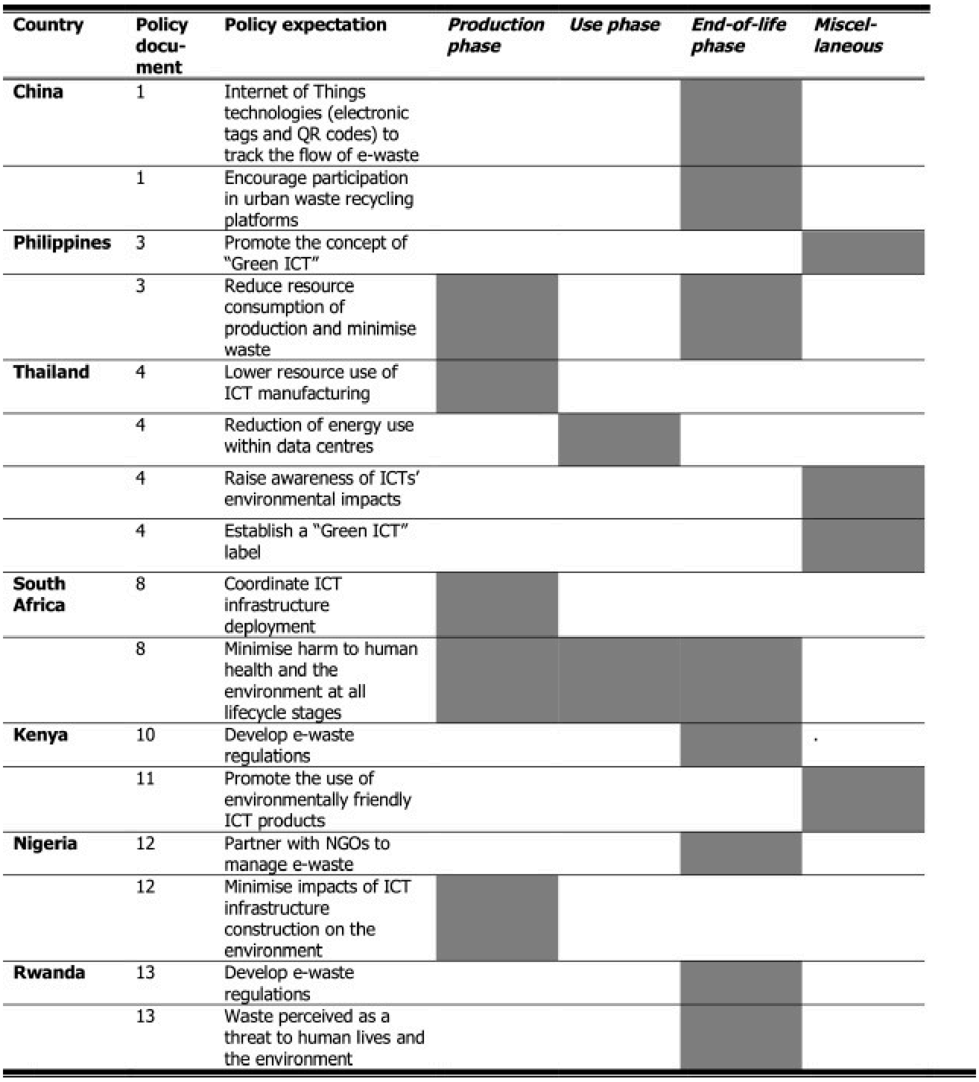
In the second step, we analysed the coded text passages through the lens of our framework for environmental effects of ICTs in industry (Section 2.2). We assigned coded text passages to the sub-categories within the main categories of both direct and indirect effects. For instance, if policies mentioned the potential contribution of ICTs to energy efficient production, the text passage was assigned to the sub-category “resource efficiency” (indirect environmental effects). We deliberately chose not to start the reading and analysis through the lens of our framework in the first step, in order to ensure that we captured the entirety of relevant text passages. However, we found that only few expectations could not be grouped into one of the sub-categories which we had identified ex ante. These were grouped in the category “Miscellaneous”.

In the third step, we compiled and paraphrased the categorised text passages for each country in two tables, differentiating for instance between accounts of current circumstances and perceived issues on the one hand and future goals to tackle these issues on the other hand. This enabled us to identify “blind spots” (i.e. effect categories for which no expectations could be found). We additionally provided five examples for expectations on direct and indirect environmental effects of ICTs.

2.4 Results & discussion

2.4.1 Expectations about direct environmental effects of ICTs

Table 6 lists the sum of expectations on direct environmental effects of ICTs that were expressed in the digital and/or industrial policy of the respective country. Where applicable, we assigned the expectations to the fitting phase of the lifecycle (i.e. the sub-categories) that they referred to, indicated by the grey boxes in each row. All other expectations were grouped into the sub-category “Miscellaneous”. Policy expectations are abbreviated in the corresponding column in Table 6. A longer version of the paraphrased text passage from the policies is provided in Appendix B.



Country	Policy document	Policy expectation	*Production phase*	*Use phase*	*End-of-life phase*	*Miscellaneous*
China	1	Internet of Things technologies (electronic tags and QR codes) to track the flow of e-waste			▨	
	1	Encourage participation in urban waste recycling platforms			▨	
Philippines	3	Promote the concept of "Green ICT"				▨
	3	Reduce resource consumption of production and minimise waste	▨		▨	
Thailand	4	Lower resource use of ICT manufacturing	▨			
	4	Reduction of energy use within data centres		▨		
	4	Raise awareness of ICTs' environmental impacts				▨
	4	Establish a "Green ICT" label				▨
South Africa	8	Coordinate ICT infrastructure deployment	▨			
	8	Minimise harm to human health and the environment at all lifecycle stages	▨	▨	▨	
Kenya	10	Develop e-waste regulations			▨	
	11	Promote the use of environmentally friendly ICT products				▨
Nigeria	12	Partner with NGOs to manage e-waste			▨	
	12	Minimise impacts of ICT infrastructure construction on the environment	▨			
Rwanda	13	Develop e-waste regulations			▨	
	13	Waste perceived as a threat to human lives and the environment			▨	

Table 6: Policy expectations regarding direct environmental effects of ICTs. Note: Unless otherwise stated, the expectations represent goals that were mentioned in the policies.

The results highlight that all countries referred to direct effects of ICTs within their respective policies. Especially the end of the lifecycle of ICT products received attention (e.g. e-waste). In general, direct environmental effects of ICTs as well as anticipated goals are hardly quantified. Hence, policy expectations appear in the form of generic goals, but they often fail to elaborate what constitutes the concrete environmental problem of ICTs in the country's context.

2.4.1.1 Example 1: e-waste and legal frame

The policies of Kenya, Nigeria, and Rwanda emphasise the respective country's need for an improved legal framework and regulations for ICTs' related environmental impact, particularly addressing the disposal of ICT devices. The proposed measure is relevant not only in the light of e-waste that is being imported into these countries (Heeks, Subramanian and Jones 2015), but also given the fact that e-waste production is beginning to grow within the region of Sub-Saharan Africa (Baldé et al. 2017). Although not explicitly addressed in the policies we analysed, similar trends and concerns can also be perceived in other countries. China, having itself become the largest producer of e-waste in the world with a large and flourishing informal e-waste market (Orlins and Guan 2016), banned foreign e-waste imports from 1 January 2018 (Fu et al. 2018).

Reflecting upon what has happened since the publication of the policies until our analysis in 2019, all three Sub-Saharan African countries have either drafted (Kenya, Nigeria) or published (Rwanda) national e-waste management policies. For instance, in Kenya the National Environment Management Authority (NEMA) drafted the "Environmental Management and Coordination (E-waste Management)" regulations 2013 (Kenya 2013). However, it is also important to strengthen concerted efforts on the national level to politically address and enforce measures of e-waste management. Even if countries established frameworks for e-waste management, it is crucial to also develop the means to enforce compliance with laws, which are often not in place (Baldé et al. 2017). Thus, having a legal framework in place can only be viewed as a necessary first step, but not as a sufficient condition for the effective public regulation of e-waste.

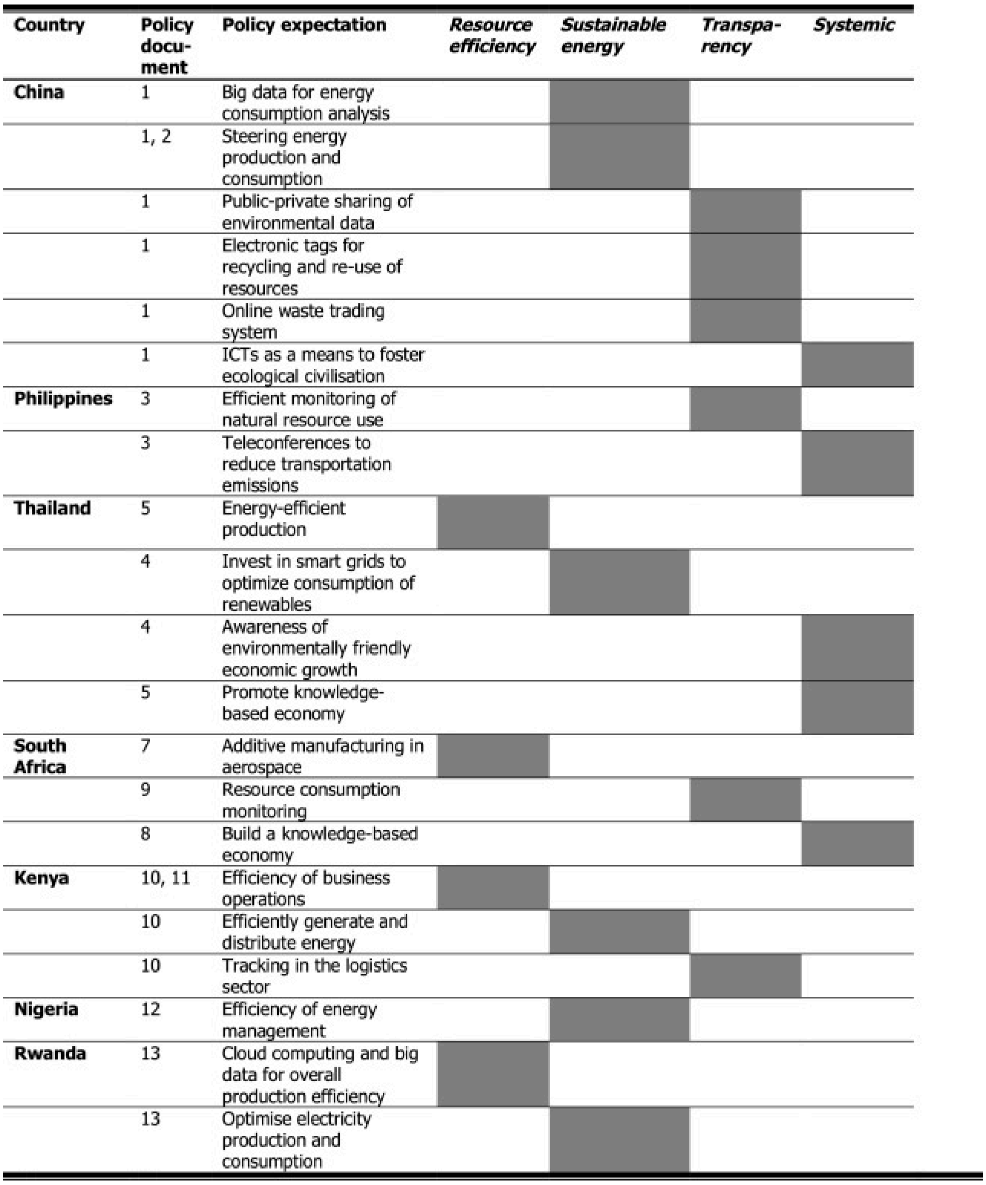
2.4.1.2 Example 2: Green ICT

By contrast, the environmental impacts of ICTs which occur during the production and use phases are less frequently considered in the analysed policies. Particularly, the increasing demand for raw materials and electricity that are accompanied by a growing use of ICTs in industry are not mentioned. Moreover, the policies expressed limited awareness of the increases in electricity demand of underlying ICTs infrastructure such as data centres and servers. The content analysis revealed only singular assertions regarding these issues. Hence, we consider this a major blind spot of various policies that we analysed.

The lack of specificity of the analysed policies regarding the direct environmental impacts of ICTs at all stages of their lifecycle is also concerning, given that multiple policies mentioned the goal of promoting labels for "Green IT" or "Green ICT" (Table 3). These labels emphasise the need for an environmentally friendly design and use of ICT (Ozturk et al. 2011). Thailand, Philippines, Nigeria, and Rwanda propose the promotion of Green ICT labels in their ICTs policies. However, no specific definitions of what Green ICTs are and what conditions they have to fulfil are given. Clear objectives regarding the extent to which industry should foster and use Green ICTs are lacking.

2.4.2 Expectations about indirect environmental effects of ICTs

Table 7 lists the sum of expectations on indirect environmental effects of ICTs that were expressed in the digital and/or industrial policy of the respective country. We grouped the expectations into the subcategories of "resource efficiency", "sustainable energy", "transparency" and "systemic effects", indicated by the grey boxes in each row. Policy expectations are abbreviated in the corresponding column in Table 5. A longer version of the paraphrased text passage from the policies is provided in Appendix B.



Country	**Policy document**	**Policy expectation**	***Resource efficiency***	***Sustainable energy***	***Transparency***	***Systemic***
China	1	Big data for energy consumption analysis		■		
	1, 2	Steering energy production and consumption		■		
	1	Public-private sharing of environmental data			■	
	1	Electronic tags for recycling and re-use of resources			■	
	1	Online waste trading system			■	
	1	ICTs as a means to foster ecological civilisation				■
Philippines	3	Efficient monitoring of natural resource use			■	
	3	Teleconferences to reduce transportation emissions				■
Thailand	5	Energy-efficient production	■			
	4	Invest in smart grids to optimize consumption of renewables		■		
	4	Awareness of environmentally friendly economic growth				■
	5	Promote knowledge-based economy				■
South Africa	7	Additive manufacturing in aerospace	■			
	9	Resource consumption monitoring			■	
	8	Build a knowledge-based economy				■
Kenya	10, 11	Efficiency of business operations	■			
	10	Efficiently generate and distribute energy		■		
	10	Tracking in the logistics sector			■	
Nigeria	12	Efficiency of energy management		■		
Rwanda	13	Cloud computing and big data for overall production efficiency	■			
	13	Optimise electricity production and consumption		■		

Table 7: Policy expectations regarding indirect environmental effects of ICTs. Note: Unless otherwise stated, the expectations represent goals that were mentioned in the policies.

We find that all policies include expectations regarding indirect environmental effects of ICTs. The degree to which a particular policy addresses one of the identified sub-categories varies greatly between countries. Expectations rarely include more than assumptions about singular (causal) effects and applications of ICTs. Neither do they portray linkages of how different technologies can influence a specific environmental issue in industry, nor do they assess the variety of environmental impacts that a specific ICT may have.

2.4.2.1 Example 3: 3D print in the aerospace industry in South Africa

Regarding the sub-category of "resource efficiency", the content analysis revealed various goals of using ICTs to increase the overall efficiency of industrial production in order to decrease its environmental footprint. Promoting additive manufacturing for resource efficient production is one case that stands out among the few expectations mentioned within the South African policy for its relatively detailed description of application. Besides specifying the technology, the aerospace industry is also mentioned as a particular field in which environmental benefits may occur. However, as with other statements, the policy lacks quantified goals or estimates of potential savings. Still, it implicitly addresses the twofold advantages of decreased material consumption in manufacturing and lower fuel consumption of aeroplanes as a direct consequence (Huang et al. 2016) by focusing on the aerospace industry. Also, the negligible size of the aerospace industry in South Africa (0.2 % of manufacturing GDP in 2016, see Industrial Policy in Appendix B, can be linked to the current development state of 3D printing. Given the currently low diffusion of additive manufacturing on a global scale (Gebler, Schoot Uiterkamp and Visser 2014), the envisioned application in a smaller domestic sector may present a reachable goal. However, obstacles for the adoption of additive manufacturing in terms of infrastructure, as well as environmental impacts of high customisation of goods, potentially leading to higher resource use, are not elaborated.

2.4.2.2 Example 4: renewable energy proliferation in Kenya, Rwanda, and China

Regarding the sub-category of “sustainable energy”, Kenyan and Rwandan policies included general remarks on the role of ICTs for energy production and consumption, but statements are mostly lacking assumptions as to how this is important in the country’s context as well as explanations as to how ICTs may contribute to more environmental sustainability in the energy sector. In Rwanda, the Ministry of Infrastructure (MININFRA) recently commissioned large-scale PV solar plants (MININFRA, 2018). Hence, the importance to efficiently use volatile energy sources, aided by ICTs, is likely to increase and crucially hinges on the deployment of adequate infrastructure (Buchana and Ustun 2015). Thus, it should be considered that ICT-enabled renewable energy integration could pave the way towards improved environmental performance of the sector if policy objectives are specified and implemented.

The Chinese policy, on the other hand, expresses high expectations regarding the role of big data to be a key tool in analysing energy demand and supply and scheduling industrial activity (demand side management, see, for instance, Liu et al. (2015) and Zhou and Yang (2015). Not only shall private and public sectors cooperate on energy production, but it is also expected that consumers will be involved in the decentralised, distributed energy network with a particular focus on renewable energy. The goal of sector coupling between electricity production and the transport sector through electric vehicles and the plan of increased online trading of electricity underline the intention expressed in the Chinese policy to strongly integrate the internet in the energy sector.

With energy in China being largely generated by coal-fired plants, (IEA 2017a) the country has a high level of carbon dioxide output per unit of GDP. The Chinese government has pledged to reduce the intensity of carbon dioxide in industrial output, with the energy sector being a major leverage to achieve this goal. Benefitting from the integrative function of ICTs at the interface between energy production and consumption, demand side management and sector coupling have the potential to enable better integration of renewable energies in the Chinese energy mix. The policy expectations, however, seem to build on the assumption of quick technological advances (“breakthroughs”) and seamless transition from the current “offline” energy system to an energy system largely incorporating ICTs. Potential structural barriers, such as a lack of investment in the grid to absorb renewable energy installation, (Fischer 2018) are not discussed. Furthermore, no specific renewable energy targets are mentioned and questions about uptake of new technologies in industry and among consumers are not posed.

2.4.2.3 Example 5: digital monitoring of resource use in China

Regarding the sub-category of "transparency", the Chinese policies put emphasis on the use of big data in the monitoring and optimisation of natural resources used in industrial production. To increase transparency, the Chinese government fosters the sharing of data between public and private stakeholders on resources and the environment. For instance, one goal is to collect data through Internet of Things technologies and electronic tags to track waste and set up a trans-sectoral information exchange on resource use.

China has already made several unsuccessful attempts to create an integrated waste recycling system (Xue et al. 2019). The coexistence of formal and informal waste treating, a lack of reliable information about waste content, weak enforceability of legislation and a lack of economic incentives have been hindering progress (Fu et al. 2018; Su et al. 2013). If properly implemented, ICTs could contribute to providing reliable data and thus overcome some of these obstacles. We therefore consider this approach as one of the more promising example of how ICTs are envisioned as a solution for issues of environmental sustainability. However, it remains unclear how positive effects can be achieved on a larger scale beyond trial industrial parks where they are currently implemented. Moreover, technical and economic challenges (such as large-scale, automated data processing and economic profitability) of digital monitoring deployment would need to be addressed.

Regarding the sub-category "systemic effects", there is very little awareness of systemic effects of ICTs in the analysed policies. The Thai and the Chinese policy suggest a transformative potential in ICTs for environmentally-friendly growth. However, there are no direct mentions of rebound effects or other emerging risks in the context of an increased uptake of ICTs in industry. In South Africa and Thailand, digital strategies are centred around the idea of knowledge-based economies and societies, but it is not specified how the concept of a knowledge economy should help reduce resource and energy intensity of industry.

2.5 Concluding remarks

In this paper, we explored policy makers' expectations in seven African and Asian countries regarding the impacts of the proliferation of ICTs in industry for environmental sustainability. Our analysis showed that policies included some degree of awareness of environmentally detrimental effects related to ICTs particularly focusing on the disposal of ICTs, but in many instances omitted issues related to the production and use of ICTs. Hence, there are several gaps in the recognition of direct environmental effects. Although goals are set out to promote standards for environmentally friendly ICT products, these do not seem to be linked systematically to resource and energy consumption during the production and use of these products. With many

LMIC aspiring to grow local ICT manufacturing, we highlight the benefit of integrating these considerations in order to foster more environmentally friendly production of ICTs.

Furthermore, expectations regarding positive indirect effects of ICTs were found in the policies of each country. Similar to direct effects, expectations were rarely specific. We observed mostly one-dimensional expectations and point to the lack of relatedness between direct and indirect effects, for instance when efficiency gains enabled by the use of digital technology were not weighed against resource consumption of the discussed technology. Expectations regarding systemic effects of ICTs were only loosely connected to environmental sustainability in the analysed policies. We suggest that the potential occurrence of rebound effects should be brought into stronger focus of digital and industrial policymaking. Efficiency gains from technological progress have failed to decrease the overall environmental burden of industrial production in the past due to rebound effects, e.g. where increases in energy efficiency induced by ICTs were overcompensated and eventually resulted in increased overall energy demand. Currently, systemic feedbacks from ICT-enabled efficiency gains seem to be neglected both in industrial and digital policies. This raises the risk of promoting ICTs as a panacea for environmental issues.

The design of our study comes with some limitations. Expectations from the selected policy documents are not generalisable to other countries in the respective world regions. Having excluded policies that did not express any expectations regarding the impacts of ICTs on environmental sustainability should not deviate attention from the fact that 25 of the 38 screened policies did not, or only barely, cover environmental issues of the digital transformation in industry at all. Even in those countries where explicit mentions have been made, policy expectations are no evidence for subsequent political action and conditions on the ground. Therefore, future research could extend this work by providing context-specific assessments of if, how and by whom ICT-related goals for environmental sustainability in industry are developed, implemented and achieved.

National policies play an important role in shaping industrial development and the digital transformation. In many countries, the digital transformation of industrial production is still in its infancy. Likewise, the industrial sector itself is still being developed in many LMIC. Hence, this may be a crucial point in time to lay the foundation for a digital and industrial transformation that has environmental sustainability at its core. To this end, science and policy makers need to engage into a more active exchange on the certainties and uncertainties related to the impact of the digital transformation on environmental sustainability in industry. While policy makers need to deal with an increasing amount of scientific research, science itself is still very much undecided as to how the digital transformation will impact environmental sustainability of production in a given context. Our study pointed at the specifics of each country's situation – including the stage of industrial development and the degree of digitalisation – that should be investigated further in future case studies.

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Author statement

The authors have contributed equally to each section of the paper.

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Appendix

Appendix A: Excluded policies due to a lack of thematic fit

Country	Name of the document	Year	Author
East Asia and Pacific			
Cambodia	Cambodia Industrial Development Policy 2015 –2025	2015	Royal Government of Cambodia
Cambodia	Summary on Cambodian ICT Masterplan 2020	2014	Royal Government of Cambodia
Malaysia	Industry4WRD - National policy of Industry 4.0	2018	Ministry of International Trade and Industry
Myanmar	Myanmar Industrial Development 2017	2016	Ministry of Industry
Papua Neuguinea	National Information and Communications Technology (ICT) Policy	2008	Department of Communication and Information
Philippines	DTI Prosperity Plan 2022	2019	Department of Trade and Industry
Vietnam	Viet Nam Industrial Strategy Period 2011-2020	2014	Ministry of Industry and Trade
Sub-Saharan Africa			
Botswana	ICT Master Plan	2012	Botswana Parliament
Cameroon	Strategic Plan for a digital Cameroon 2020	2016	Ministry of Posts and Telecommunications
Eswatini	ICT Master Plan	2010	Parliament of the Kingdom of Swaziland
Ethiopia	The National Information and Communication Technology Policy and Strategy	2009	Federal Democratic Republic of Ethiopia
Gambia	The Gambian ICT4D-2021 Plan	2008	Department of State for Communication, and Information Technology
Liberia	National Telecommunications & ICT Policy	2010	Ministry of Posts & Telecommunications
Malawi	National ICT Masterplan 2014-2031	2014	Government of Malawi
Mauritius	National Information & Communication Technology Strategic Plan	2011	Ministry of Information and Communication Technology
Namibia	Strategic ICT Plan 2017-2022	2017	Ministry of Information and Communication Technology
Sierra Leone	National ICT Policy	2009	Ministry of Information and Communications
Somalia	ICT Policy & Strategy	2019	Ministry of Post, Telecommunications & Technology
Tanzania	Integrated Industrial Development Strategy 2025	2011	Ministry of Industry and Trade
Tanzania	National ICT Policy	2016	Ministry of Works, Transport and Communication
Uganda	National Information and Communications Technology Policy	2014	Ministry of Information and Communications Technology
Zambia	National Industrial Policy	2018	Ministry of Commerce, Trade and Industry
Zambia	ICT Masterplan	2010	National Assembly of Zambia
Zimbabwe	Industrial Development Policy 2012-2016	2012	Ministry of Industry and Commerce
Zimbabwe	National Policy for ICT 2016-2020	2016	Ministry of ICT, Postal and Courier Services

Table 8: Excluded policies due to a lack of thematic fit

Appendix B: Extended paraphrased policy expectations

Direct environmental effects

Thailand

- Lower resource use of ICT manufacturing: Lower the natural resource use of ICT manufacturing.
- Reduction of energy use within data centres: Reduce the energy use within data centres.
- Raise awareness of ICTs' environmental impacts: Raise awareness of ICT impacts on the environment.
- Establish a "Green ICT" label: Establish a "Green ICT" label for products manufactured in the country.

Philippines

- Promote the concept of "Green ICT": Promote the concept of "Green ICT".
- Reduce resource consumption of production and minimise waste: Reduce the energy and resource consumption of ICT production and minimise waste production of ICTs.

China

- Internet of Things technologies (electronic tags and QR codes) to track the flow of e-waste: Support the use of Internet of Things technologies such as electronic tags and QR codes to track the flow of e-waste.
- Encourage participation in urban waste recycling platforms: Encourage internet companies to participate in the construction of urban waste recycling platforms, and innovate the recycling model of renewable resources.

South Africa

- Coordinate ICT infrastructure deployment: Coordinate ICT infrastructure deployment in order to minimise negative effects of digging and trenching.
- Minimise harm to human health and the environment at all lifecycle stages: Ensure that the design, use, and disposal of ICTs does not cause harm to human health or the environment.

Kenya

- Develop e-waste regulations: Develop regulations for recycling and disposal of used ICT equipment.
- Promote the use of environmentally friendly ICT products: Promote the use of environmentally friendly ICT products.

Nigeria

- Partner with NGOs to manage e-waste: Partner with NGOs and donor agencies that deal specifically with control, management, and disposal of e-waste.
- Minimise impacts of ICT infrastructure construction on the environment: Negative impacts of ICT infrastructure construction on the environment (CO2 emissions, radioactivity, e-waste) is perceived as an issue.

Rwanda

- Develop e-waste regulations: Development of legal and regulatory framework to address e-waste.
- Waste perceived as a threat to human lives and the environment: Waste generated by a growing number of devices is perceived as a serious threat to human lives and the environment.

Indirect environmental effects

Thailand

- Energy efficient production: Promote the use of ICTs to increase energy efficiency of production and for environmental protection measures.
- Invest in smart grids to optimize consumption of renewables: Support investment in smart grids to promote renewable energy consumption.
- Awareness of environmentally friendly economic growth: Increase awareness for the role of ICTs in promoting environmentally friendly economic growth.
- Promote knowledge-based economy: Use the proliferation of ICTs to transform the country into a knowledge-based economy and society.

Philippines

- Efficient monitoring of natural resource use: Use ICTs to monitor the environment and natural resources more effectively and efficiently.
- Teleconferences to reduce transportation emissions: Promote internet-enabled teleconferences to decrease the environmental effects of transportation.

China

- Big data for energy consumption analysis: Use big data for energy consumption analysis.

- Steering energy production and consumption: Develop digitally-enabled grid of energy production and consumption among different actors to optimise renewable energy consumption and overall efficiency of energy production and consumption.
- Public-private sharing of environmental data: Share of data between public and private stakeholders on resources and the environment.
- Electronic tags for recycling and re-use of resources: Use the IoT and electronic tags to track e-waste and to improve recycling and re-use of resources.
- Online waste trading system: Establish an online waste trading system.
- ICTs as a means to foster ecological civilisation: Systemically integrate the internet to transform industrial production and facilitate the construction of an ecological civilisation.

South Africa

- Additive manufacturing in aerospace: Use additive manufacturing to increase the efficiency of production in the aerospace industry.
- Resource consumption monitoring: Enable resource consumption monitoring using ICTs.
- Build a knowledge-based economy: Build an inclusive knowledge-based economy against the background of an unsustainably resource-intensive economy.

Kenya

- Efficiency of business operations: Use ICTs and mobile communication to increase the overall efficiency of business operations.
- Efficiently generate and distribute energy: Acknowledgement that ICTs are a valuable tool in the efficient generation, distribution, and utilisation of energy.
- Tracking in the logistics sector: Use ICTs in the trade, transport, and logistics sector for tracking and monitoring purposes.

Nigeria

- Efficiency of energy management: Use the proliferation of ICTs to increase the efficiency of energy management and decrease environmental degradation.

Rwanda

- Cloud computing and big data for overall production efficiency: Use of cloud computing and big data to increase overall resource efficiency of production.
- Optimise electricity production and consumption: Investigate the potential of ICTs to optimise electricity production and consumption.

3

Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry

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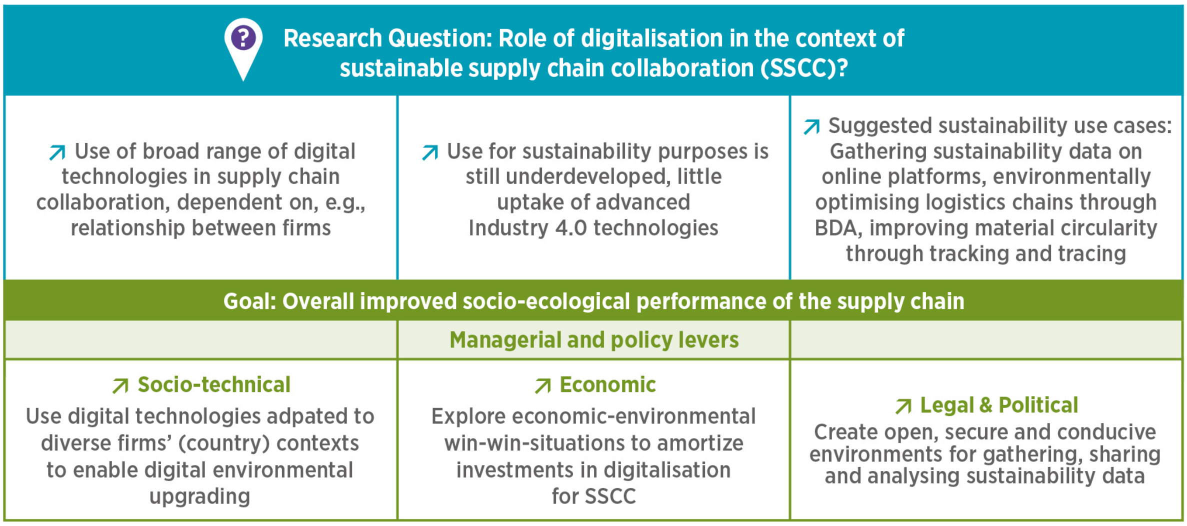
Abstract

With the proclaimed advent of Industry 4.0 in supply chains, digitalisation is expected to restructure the ways in which buying firms and suppliers in supply chains collaborate, including on sustainability issues. Digital technologies are expected to foster information exchange and facilitate collaboration on sustainability issues between firms. Yet, there is limited empirical evidence explaining the role of digitalisation in the context of sustainable supply chain management. This qualitative study examines digitalisation in the electronics supply chain and its implications for sustainable supply chain collaboration (SCC). We focus on environmental sustainability aspects, such as environmental data gathering and analysis, material and energy use, and emissions and waste in the supply chain. We conducted 18 interviews with representatives from international electronics buying firms and Chinese suppliers to explore a) how digital technologies are currently used in SCC, and b) which opportunities, risks, and obstacles are associated with digitalisation in sustainable SCC. Our results indicate that a broad range of digital technologies are used in SCC depending on firms' relationships, but their use for sustainability purposes is still underdeveloped. Digitalisation was viewed as positive for sustainability by most firms, e.g. using big data analytics for energy management and eas-

ing the transfer of sustainability knowledge in the chain (i.e. environmental upgrading). We argue, however, that if firms do not strategically prioritise addressing sustainability through digitalisation in collaboration, digitalisation-related efficiency improvements will either not be achieved by firms, e.g. due to data sharing concerns, or tend to be overshadowed by the negative indirect effects of digitalisation, such as rebound effects. We propose three political and managerial levers to enhance the overall socio-ecological performance of the supply chain.



Research Question: Role of digitalisation in the context of sustainable supply chain collaboration (SSCC)?

↗ Use of broad range of digital technologies in supply chain collaboration, dependent on, e.g., relationship between firms

↗ Use for sustainability purposes is still underdeveloped, little uptake of advanced Industry 4.0 technologies

↗ Suggested sustainability use cases: Gathering sustainability data on online platforms, environmentally optimising logistics chains through BDA, improving material circularity through tracking and tracing

Goal: Overall improved socio-ecological performance of the supply chain

Managerial and policy levers

↗ Socio-technical
Use digital technologies adpated to diverse firms' (country) contexts to enable digital environmental upgrading

↗ Economic
Explore economic-environmental win-win-situations to amortize investments in digitalisation for SSCC

↗ Legal & Political
Create open, secure and conducive environments for gathering, sharing and analysing sustainability data

Figure 5: Graphical Abstract, source: own elaboration, RIFS illustration

Keywords

Sustainable supply chain management, Global value chains, Environmental upgrading, Industry 4.0, Digitalisation, Big data analytics, Artificial intelligence, Electronics

3.1 Introduction

Digitalisation, defined as the increasing development and application of information and communication technologies (or digital technologies), is expected to transform collaboration in global supply chains (IEA 2017a; WBGU 2019b). With firms along the supply chain using digital technologies, digitalisation can facilitate data and information exchange across company borders and enable better collaboration between supply chain partners (Vanpoucke, Vereecke and Muylle 2017). In recent years, research and business interest has shifted to advanced digital technologies, as envisioned in the concept of "Industry 4.0". Industry 4.0 is characterised by the implementation of its core concepts, such as cyberphysical systems, the internet of things (IoT), big data analytics (BDA), artificial intelligence (AI), cloud computing, and additive manufacturing, in and across firms (Aoun et al. 2021; Han and Trimi 2022; Li, Dai and Cui 2020; Martinelli, Mina and Moggi 2021). Industry 4.0 technologies are expected to facilitate supply chain optimisation in real time, create interconnected production processes, and allow for customisation of production, products, and services along the supply chain (Bag et al. 2018; Bányai 2018; Beier et al. 2020c; Birkel and Hartmann 2019).

At the same time, firms are required to take more social and environmental responsibility along their entire supply chain. The German Supply Chain Act ratified in June 2021, for instance, obliges companies to improve human rights compliance in global supply chains and adhere to certain (although limited) environmental standards, i.e. the Minimata Convention on Mercury, the Stockholm Convention on Persistent Organic Pollutants, and the Basel Convention on Hazardous Waste (BMZ 2021; Bundesregierung 2021). Increasing accountability poses challenges to companies in supply chains, as compliance with regulations requires knowledge from different actors in the supply chain (Seuring and Gold 2013). Collaboration can be considered a critical success factor for sustainable supply chain management (Tseng et al. 2019). Against this backdrop, stakeholders such as international organisations, private sector associations, and governments hope that digitalisation will contribute to more sustainable supply chains, e.g., by enhancing the monitoring of environmental performance and managing resource efficiency in value chains (UNCTAD 2019).

Various disciplines examine the role of digitalisation in sustainable supply chain collaboration (SCC). In the supply chain management literature, risks and opportunities of digitalisation for sustainability on the firm and supply chain level (often in the Global North) are being investigated (Bag et al. 2020), as well as how firms collaborate on sustainability in the supply chain (Sellitto et al. 2019). In the global value chains literature, implications of digitalisation for production geography across the globe (Ferrantino and Koten 2019; Ganne and Lundquist 2019; Laplume, Petersen and Pearce 2016), as well as governance of value chains for (environmental) sustainability in the Global South (Achabou, Dekhili and Hamdoun 2017; Golini et al. 2018), are being scrutinized. Yet, there is little empirical evidence at the intersection of these research fields linking insights from supply chain management and the global value chains literature on digitalisation for sustainability in SCC. However, in our view, this intersection should receive research attention in order to specify the framework conditions that would allow expected potentials of digitalisation for sustainability to be realised and potential risks to be mitigated – along the supply chain in the Global North and the Global South.

In this qualitative, explorative study, we therefore analyse current digitalisation practices in the electronics supply chain and their implications for sustainable SCC from the perspective of both buying firms and suppliers. We focus on environmental sustainability aspects of sustainable SCC (for instance, energy and material use in the supply chain). Among the set of Industry 4.0 technologies, we chose to investigate interview partners' perceptions of big data analytics and artificial intelligence due to its associated functionalities. In the context of the analysis of heterogeneous data sources from complex value chains, technologies for the handling and (semi-)automatic recognition of patterns and relationships from large amounts of data appear to be particularly relevant (Beier et al. 2020a; Jeble et al. 2018; Mani et al. 2017). We pose two research questions of an explorative nature:

- RQ1: How are digital technologies currently used in SCC?
- RQ2: What are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

We conducted 18 expert interviews (eight written, ten in oral format) with supply chain managers from international electronics buying firms (headquartered in Europe, except for one Japanese firm) and Chinese suppliers. The focus on Chinese suppliers was chosen because China is the largest exporter of electronics (see 6). Moreover, Chinese firms are in a special position to harness digitalisation for sustainable SCC due to a conducive policy environment (Kunkel and Matthess 2020). They are also likely to increasingly impact sustainability aspects in other emerging countries further upstream in the value chain.

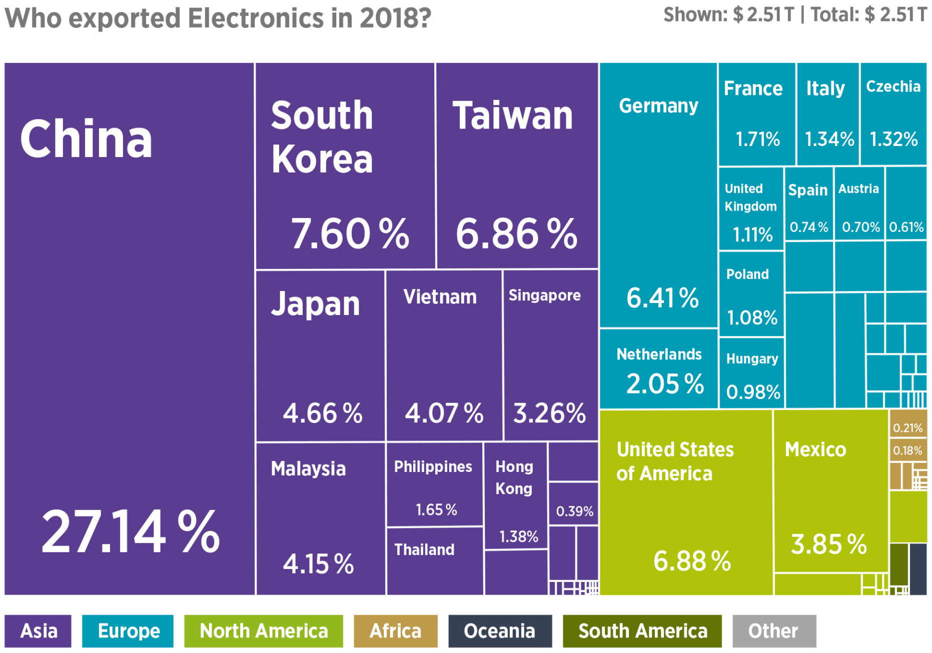


Figure 6: Electronics exports in 2018; source: RIFS illustration based on Hausmann et al. (2023).

This paper should make at least three contributions to the existing literature: First, we identify opportunities, risks, and obstacles related to digitalisation for sustainable SCC as perceived by practitioners in international buying firms and Chinese supplier firms in the electronics sector. Our aim is to contrast both perspectives and identify both sides' perceived opportunities of and obstacles to digitalisation for sustainable SCC. Second, we identify envisioned and implemented use cases from the interviews, e.g., of the application of big data analytics (BDA)[11] for sustainable SCC, and thereby contribute to the scarce literature on empirical examples of the use of Industry 4.0 technologies for sustainability in the supply chain. Last, by connecting two largely separate strands of literature, namely, on sustainable supply chain management and the global value chain, we link the perspective of management to foster sustainable SCC and the broader governance perspective of (digital) environmental upgrading.

3.2 Theoretical background: sustainability and digitalisation in supply chain collaboration (SSC)

In this section, we first describe the theoretical lens through which we analyse environmental sustainability in SCC. Second, we present our concept of digitalisation in SCC by defining categories of digital maturity. Third, we link sustainability and digitalisation in SCC. Finally, we formulate our research questions.

3.2.1 Sustainable SCC and environmental upgrading

This study focuses on sustainable SCC (supply chain management literature) and integrates perspectives on environmental upgrading in global value chains (global value chains literature). We define sustainable supply chain collaboration (SCC) as interactions of two or more parties (mainly, but not limited to, firms) in the supply chain during processes of shared planning, sourcing, making, delivering, and returning of goods and services to improve performance in reaching sustainability goals. It comprises product- and process-related, as well as organisational improvements (Blome, Hollos and Paulraj 2014; Vachon and Klassen 2006). We define "environmental upgrading" as the process of enhancing the environmental performance of the value chain with regard to products and processes through changes on the technological, social, and organisational levels (Poulsen, Ponte and Sornn-Friese 2018). The two literature strands identify similar and often mutually enriching perspectives on the risks and opportunities of digitalisation for more sustainable SCC. Arguably, sustainable SCC focuses more on the collaboration between firms in the supply chain, while environmental upgrading focuses on the broader governance and institutional conditions of value chains that need to be met to ensure better environmental performance of firms. Figure 7 shows a comparison of the two literature strands. Considering both perspectives should provide a theoretical lens through measures to foster Industry 4.0 for SCC at all levels — firm, supply chain and global level — can be conceived.

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[11] We define BDA in our interviews as a technical means to gather, manage, and analyse large volumes of unstructured data (Leveling, Edelbrock and Otto 2014).

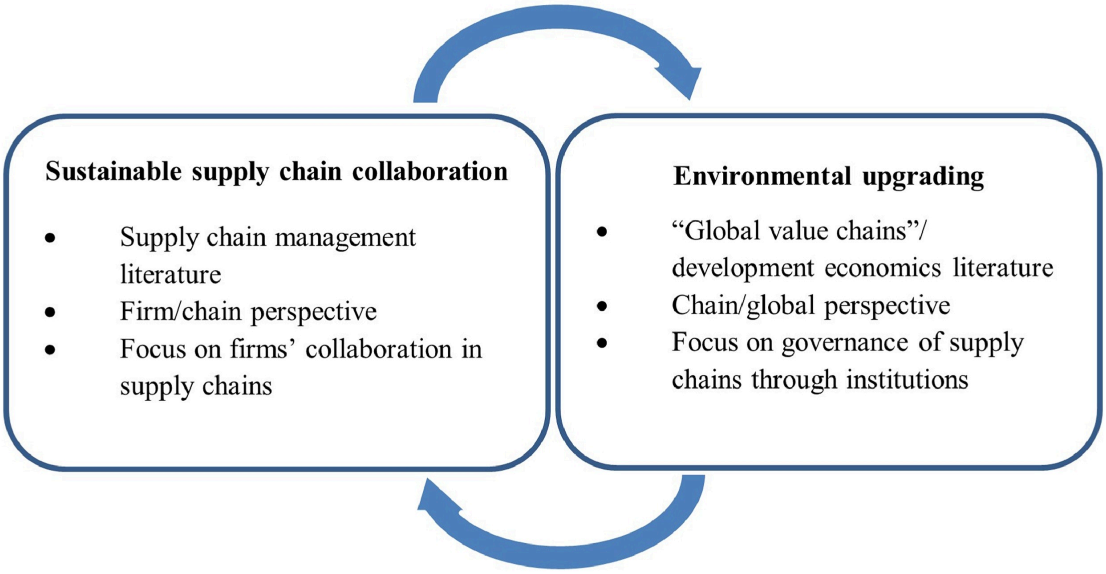


Figure 7: Comparison between concepts of sustainable supply chain collaboration and environmental upgrading; source: own elaboration.

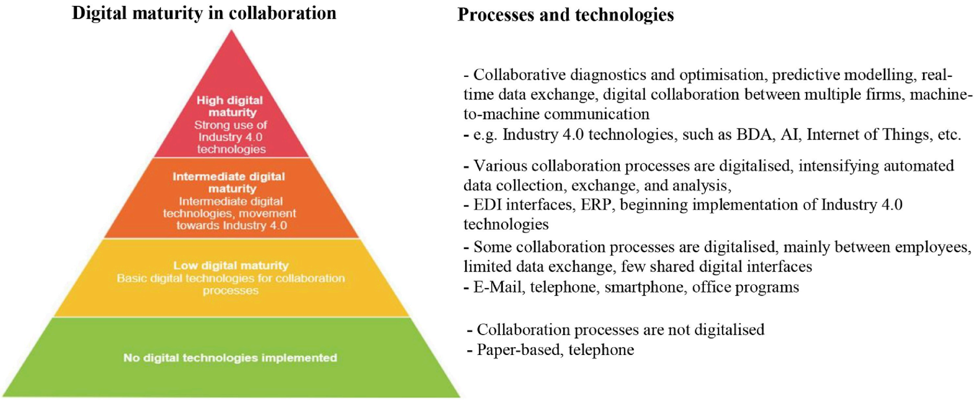
Taking a supply chain perspective, Vachon and Klassen (2006, 2008) find that collaboration fosters interorganisational learning and enhances sustainability capabilities. Sustainable SCC between supply chain partners usually includes an extensive exchange of information and knowledge, which is argued to contribute to the transmission of sustainability knowledge, standards, regulatory requirements, technology, and organisational practices between firms in the supply chain (Bai and Sarkis 2010; Vachon and Klassen 2006). However, supplier collaboration with sustainability aims does not necessarily lead to more sustainability in practice. In their analysis of 139 Dutch food and beverage processors, Grekova et al. (2016) found that collaboration with suppliers had not helped brand-name companies improve the sustainability of their internal processes. Yet, it had led to cost savings through the benefits suppliers gained from collaboration (e.g., lower prices of input materials). Thus, the positive effect of SCC on sustainability seems to be mediated by various factors, such as organisational and technological factors (Beltrami et al. 2021).

Taking a global value chains perspective, similarly, information and knowledge exchange between firms is argued to enable firms to environmentally upgrade to more environmentally friendly products, processes, and organisational practices (De Marchi and Di Maria 2019). Particularly, there is a focus on the role of "lead firms", typically from the Global North, in transmitting technologies and knowledge about environmental standards and policies to suppliers as well as enforcing environmental governance strategies in global value chains, especially in the Global South (Khattak and Pinto 2018). However, it has been argued that adopting standards and practices passed along the value chain may also lock suppliers into technologies and skills that do not support the development of strategic capabilities for environmental upgrading. Buyers may not want suppliers to build their own innovation capacity and obtain larger shares of added value along the value chain (De Marchi, Giuliani and Rabellotti 2018). Such challenges from the perspective of suppliers in countries in the Global South have only received limited attention in the literature (Khan, Ponte and Lund-Thomsen 2020).

In sum, there appear to be trade-offs between individual firms' interest in sustainable SCC and the optimal trajectory for environmental upgrading from a governance perspective. The existing literature points to diverse stakeholders' contexts and needs from the Global North and South that should be accounted for if sustainable SCC is going to lead to an overall improved socio-ecological performance of the supply chain. The next question is then: what role does digitalisation play in all this?

3.2.2 Digitalisation in SCC

To specify to what extent companies use digital technologies in SCC, we suggest a stylised categorisation of different levels of digital maturity. Digital maturity can be defined as "the status of a company's digital transformation" (Chanias and Hess 2016). However, digital maturity models are generally not well scientifically founded (Thordsen, Murawski and Bick 2020) and lines between categories are blurry. In Figure 8, we construct a stylised categorisation of digital maturity in collaboration. Differentiating between levels of digitalisation allows us to accommodate different types of digital technologies in further analyses, e.g., "basic" digital technologies, such as e-mail services, as well as (envisioned) "advanced" Industry 4.0 technologies, such as BDA and IoT.



- Collaborative diagnostics and optimisation, predictive modelling, real-time data exchange, digital collaboration between multiple firms, machine-to-machine communication
- e.g. Industry 4.0 technologies, such as BDA, AI, Internet of Things, etc.

- Various collaboration processes are digitalised, intensifying automated data collection, exchange, and analysis,
- EDI interfaces, ERP, beginning implementation of Industry 4.0 technologies

- Some collaboration processes are digitalised, mainly between employees, limited data exchange, few shared digital interfaces
- E-Mail, telephone, smartphone, office programs

- Collaboration processes are not digitalised
- Paper-based, telephone

Figure 8: Stylised categorisation of digital maturity in collaboration; source: own elaboration based on Bickauske et al. (2020) and Shao et al. (2021). Note: At each digital maturity level, technologies used in the previous level are likely to continue being used, e.g., enterprises with high digital maturity are likely to continue using e-mail-based communication.

3.2.3 Digitalisation for sustainability in SCC

Digitalisation is argued to have a positive influence on sustainable supply chain management and collaboration (Bag et al. 2018; Dao, Langella and Carbo 2011; Mastos et al. 2020; Yadav et al. 2020b). Digital technology can enhance the collaboration and operational performance of the supply chain by connecting supply chain partners and fostering more proactive supply chain planning, process harmonisation, decision-making, and advanced delivery practices, as long as additional supply chain integration tactics are in place (Vanpoucke, Vereecke and Muylle 2017). Advanced Industry 4.0 technologies, in particular, are expected to solve some of the existing challenges of sustainable SCC, such as collaborating more easily with numerous supply chain partners on sustainability by managing data along supply chains through BDA (Bag et al.

2020). For instance, circular economy models are theoretically facilitated by the technological and organisational restructuring of companies and supply chains towards Industry 4.0 (De Sousa Jabbour et al. 2018; Dev, Shankar and Qaiser 2020). Several recent literature reviews give an analysis of the existing evidence regarding Industry 4.0 and sustainability in the supply chain, e.g., Beltrami et al. (2021), and Birkel and Müller (2021).

However, collaboration around sustainability, including the way in which digital technologies are used, and sustainability-related data are gathered, assessed, and exchanged by firms in supply chains deserves more research attention. A recent review of empirical case studies on the organisational effects of Industry 4.0 for sustainability, for instance, indicates that only a minority of studies have looked at the organisational implications of Industry 4.0 for environmental sustainability (Margherita and Braccini 2020). Often, environmental sustainability data, e.g., lifecycle data, are not collected on the organisational level or are not integrated in firms' existing internal information systems (Gandomi and Haider 2015). For instance, energy-saving and emission-reduction evaluation technology has been found to be isolated from existing Enterprise Resource Planning (ERP), product data management, and customer relationship management, resulting in what have been termed "enterprise information islands" (Tao et al. 2014). Collaboration, in turn, is argued to facilitate the use of digital technologies. Inter-organizational collaboration has been found to enhance the effectiveness of ERP system implementation in a study on 283 Chinese firms (Li et al. 2017). Thus, there seems to be a critical link between the success of SCC and that of digitalisation. It is useful to understand how and with which tools enterprises collaborate along the supply chain in order to identify existing collaboration channels through which sustainability data could be exchanged.

Likewise, evidence demonstrating the link between digitalisation and sustainable SCC with a focus on the Global South is still scarce (Zeng, Lee and Lo 2020). On the one hand, information technology can exacerbate existing disadvantages facing firms in emerging countries along supply chains. For instance, a lack of knowledge about data management, lack of understanding around decentralised organisational structures for chain collaborations, and high investment costs were found to be the largest hurdles for circular supply chain implementation in a study of manufacturing firms in India (Ozkan-Ozen, Kazancoglu and Mangla 2020). On the other hand, digitalisation may create new business opportunities for emerging countries, particularly in forming green supply chains (Luthra and Mangla 2018). Yang et al. (2020) point to potential synergies resulting from linking information sharing, collaboration, and sustainable supply chain management in China. Surveying 300 Chinese organisations, they find that by combining approaches to green supply chain management and "green information systems" firms' economic, operational, environmental, and social performance can be enhanced. However, the authors call for more empirical studies collecting observations from multiple countries with different cultural, political, legal, and economic contexts.

In conclusion, previous studies have reviewed the extant literature on sustainability and Industry 4.0 and have shown that opportunities for digitalisation may facilitate sustainable SCC, but have also identified risks associated with it. However, there are limited empirical studies on Industry 4.0 in supply chains focusing on the role of collaboration between supply chain partners in the Global North and Global South and relating these findings to the possibility of environmental upgrading along the value chain.

3.2.4 Conceptual framework and research questions

Following from the literature gaps identified in the preceding subsections, we formulate the following research questions (RQ):

- RQ1: How are digital technologies currently used in SCC?
- RQ2: What are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

Figure 9 provides an overview of our research concept. With RQ 1, we aim to understand the use of digital technologies in SCC in general (unrelated to sustainability), in order to gain insight into the interviewed firms' digital maturity with respect to collaboration. Based on this knowledge of firms' digital technology use, RQ 2 serves to assess to what extent our interview partners perceive links between digital technologies and sustainability in SCC. We aim to identify not only explicitly stated opportunities and risks, but also opportunities and risks that might not yet be perceived by the interview partners regarding digital technologies and collaboration. Specifically, the literature describes several opportunities where an increased use of digital technologies can strengthen sustainable SCC, as well as possible negative impacts on environmental indicators associated with the large-scale use of digital technologies in SCC, such as an increased use of energy for digitising processes. Those opportunities and risks might emerge in the future due to the way digitalisation is currently envisioned and pursued in SCC. Whether and how the positive effects could outweigh the negative effects of digital technologies is rarely subject to scrutiny. In this study, mapping practitioners' views and contextualising these with theoretical considerations help us obtain a holistic view of the likeliness that possible opportunities and risks of digitalisation will emerge in SCC and what conditions have to be in place for more sustainable SCC. Therefore, in the discussion section, we aim to develop governance measures for management and policy addressing the question of how to improve the socio-ecological performance of the supply chain. We structure the proposed measures along the dimensions "socio-technical", "economic", and "legal and political", adapted from Beltrami et al. (2021). The socio-technical dimension includes organisational and technological aspects, the economic dimension includes aspects related to firms' economic models, and the legal and political dimension includes regulatory actions and political support policies.

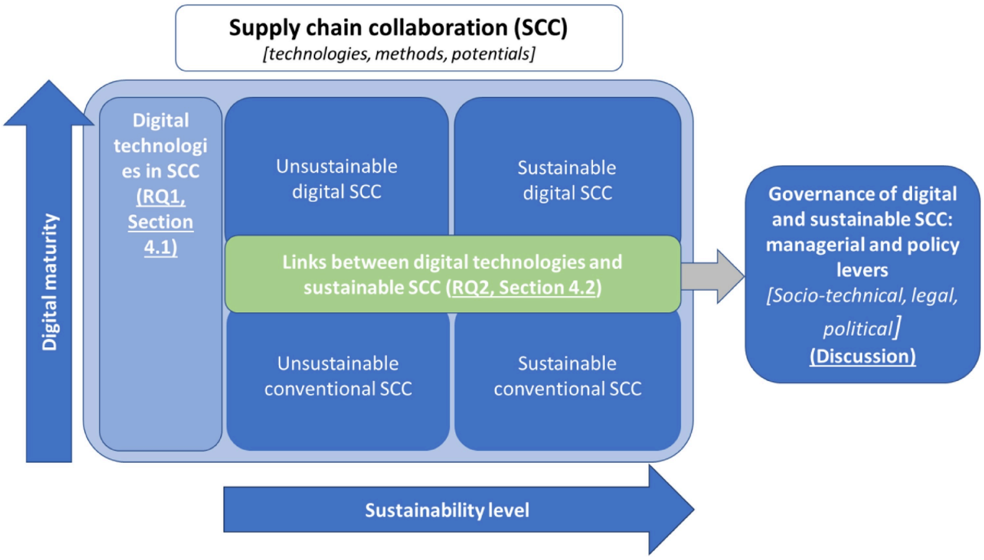


Figure 9: Theoretical concepts and research questions in this article, source: own elaboration.
Note: The quadrants in the figure show four states of SCC in a firm: a situation, where there is low digital maturity and low sustainability level (lower left), low digital maturity and high sustainability level (lower right), high digital maturity and low sustainability level (upper left), and high digital maturity and high sustainability level.

3.3 Methodology

In this section, we describe how we conducted our expert interviews and how we performed our data analysis.

3.3.1 Expert interviews

There is little data on the use of digital technologies, especially Industry 4.0 technologies, in sustainable supply chain management, particularly in emerging country contexts (Birkel and Müller 2021). Therefore, we decided to do an exploratory study using semi-structured expert interviews as well as written expert interviews to obtain basic data and trends regarding our research objective. These results can pave the way for future in-depth studies with randomised samples. The exploratory nature of our study should be considered when interpreting our results. We conducted interviews with two groups of companies in the electronics sector that we refer to as:

- “buying firms” and
- “suppliers”.[12]

This approach helped us to gather perspectives from different groups of actors in the supply

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[12] It should be noted that there are no definite boundaries that distinguish the two groups due to the complexity of supply chains, e.g., buying firms can be suppliers to other buying firms and suppliers can be buying firms to the up-stream and downstream companies they sell products to. Moreover, in the case of Chinese suppliers, some firms combined business activities as both suppliers and final sales companies. We also point to the fact that buying firms were not willing or able to bring us into contact with their direct suppliers, so we analysed suppliers in the electronics sector more broadly. Thus, the “suppliers” were not necessarily supplying the interviewed “buying firms”.

chain, i.e. international buying firms and Chinese suppliers, and contrast these perspectives to increase validity, reduce bias, and obtain a more nuanced picture from our research results.

With the buying firms, we conducted 10 semi-structured expert interviews among international buying firms (nine European, one Japanese) following a tested interview guideline (see Appendix A). The interviews took between 41 and 101 min. To reach a wider range of participants under the circumstances of the Covid-19 pandemic, we used online conferencing software to conduct the interviews. With the suppliers in the electronics sector in China, we conducted 8 interviews in written form (see Appendix B). We chose to collect written responses to avoid language barriers. The questions in the supplier questionnaire corresponded to the questions asked of the buying firms, translated into Mandarin and with minor adaptations to the specific role of suppliers, which we wanted to investigate. For instance, for some questions on the supplier questionnaire, we inquired about assessments of downstream customers and upstream suppliers. The “expert” status of our interviewees was assessed by the firms we contacted that chose their colleagues based on the introductory information we communicated.

The interviews covered the following areas:

- First, we investigated how supply chain processes are organised regarding the identification and selection of, as well as collaboration with, suppliers.
- Second, we investigated to what extent digital technologies were used in supply chain management. Specifically, we were interested in the tools used to exchange data and information and collaborate with other firms in the supply chain.
- Third, we dedicated a section of our questionnaire to the use and potential of BDA and AI in SCC, as two exemplary technologies for Industry 4.0.
- Fourth, we investigated the perceived and expected risks and opportunities of digital technologies in supply chain management for social and environmental sustainability.
- Last, we added a set of quantitative questions for which the respondents were required to assess the influence of digitalisation on sustainability aspects on a scale from -5 (“probably very negative”) to 5 (“probably very positive”).

3.3.2 Choice and characteristics of interviewees and firms

In the case of buying firms, we aimed for a systematic selection of interview partners, but bias was introduced through the irregular replies by the selected firms. In the case of suppliers, we chose convenience sampling to identify our interview partners. Although convenience sampling is likely to introduce bias to the interview results, we believe that the convenience sampling approach can be justified. It is often the only way to identify recent trends in firms, where time to participate in studies is limited and other barriers, such as confidentiality requirements, exist. We discuss the limitations of this approach in more depth in the discussion section.

Regarding buying firms, we systematically contacted companies who were affiliated with the German digital association “Bitkom”. Initially, we contacted a total of 68 companies directly via email or telephone. We reached further companies by contacting 10 associations and corporate networks in the electronics industry, as well as six civil society organisations and individuals working in the field. We usually sent/made at least one follow-up email/call if there was no response in the first round. We conducted interviews in all companies that responded positively to our request. A total of 11 companies responded positively to our request, but one company was excluded after the interview due to a lack of fit between the interviewee's position and the firm. Within each firm, we talked to leading employees from the field of supply chain management, including "Head/Director of Supply Chain Management", "Head/Director of Manufacturing Solutions" or senior management positions in SMEs/start-ups. Our oral interviews took place between July and November 2020.

Regarding suppliers, due to the language and geographic barriers, we relied on contacts from within our research team. First, based on local statistical information, we asked potential corporate contacts whether interviews and surveys could be carried out, and then based on the response opinions we further selected companies in which to conduct interviews and collect data. The interviewees from among the suppliers had more diverse occupations in the firms, namely automation engineer, purchasing/supply chain director, smart city responsible, finance and business manager, product manager, and general manager in a family-run private enterprise. However, in contrast to the buying firm interviews, the interviewees informed us that they had consulted colleagues, e.g., from the PR and OEM departments for questions they could not answer. We collected the written replies from supplying firms between November 2020 and February 2021. A detailed list with information on the interviewees and firms can be found in Appendix B.

The results from buying firms' interviews in languages other than English, i.e. German, were translated into English by the authors. Regarding the interviews conducted with supplier firms, the written interview results were translated from Chinese into English with online translators (DeepL, Bing Translator). The results of the translation were double-checked and corrected where necessary by a native speaker of the Chinese language.

3.3.3 Qualitative content analysis

We used the software "MaxQDA" to conduct a qualitative content analysis following Saldaña (2021) to transcribe and analyse the interviews. First, buying firms' interviews were transcribed from recordings taken during the interviews. Suppliers' interviews were already in written form. Second, after having obtained both sets of interviews in the form of typed documents, we proceeded equally with both groups. The intention behind using qualitative content analysis was to describe the phenomena in our research focus using categories identified in our interviews. Thus, we used content-structuring content analysis (Schreier 2015). In the first step, based on the theory-driven interview guideline, we deduced the main categories that were aligned with our research questions. In the second step, two researchers coded the passages independently and induced sub-categories where the initial scheme needed more detailed categories (Saldaña 2021). After this round of coding, the coded passages of each researcher were compared and grouped in order to identify common coding patterns. Agreement amongst researchers also increases the reliability of the coding scheme and the data analysis (Carter and Easton 2011). Where no shared understanding of a category was reached or an initial theory-driven category was not able to accommodate certain codes identified by the research team, the researchers developed further categories, and consolidated similar sub-categories. We applied the same category system to the data from the suppliers but allowed for the possibility to add categories where necessary. A final check against the theory helped us to increase the validity of our category system (Potter and Levine-Donnerstein 1999). The final category system was used to structure the results to address our two research questions. The emergent category system can be found in Appendix C. A more detailed explanation of how the research results emerged from the coding scheme can be found in Appendix D.

3.4 Results

In this section, we first describe the research results related to research question 1 focusing on digitalisation in SCC (section 3.4.1). Subsequently, we describe the research results related to research question 2 focusing on sustainability opportunities, risks, and obstacles related to digitalisation in sustainable SCC (section 3.4.2).

3.4.1 Digital technologies in SCC

In line with earlier findings, a range of digital tools are used in SCC, e. g., basic technologies such as e-mail and Excel tables, as well as more advanced digital technologies such as ERP and Electronic Data Interchange (EDI) systems. The usage of specific tools in buying firms was reported to depend on the respective supplier (II, III, IV, VI). For instance, one company reported that there was an automated, standardised data exchange with some suppliers and manual, and even paper-based, data exchange with other suppliers (IV). To determine the digital maturity level of suppliers, the use of digitalisation assessment handbooks was reported by two large buying firms (I, II). The handbook is used to assess digital maturity across different domains, such as factory operation, product tracking, general connectivity, and the adoption of IoT (I). For instance, suppliers are asked how many laptops they have on the shop floor and how many IT trainings their employees receive (I, II).

One factor in determining which digital tools are used seems to be the type of relationship the firm has with its suppliers. In transactional, loose relationships, the role of digital technologies was reported to be smaller (V, VI) than in “partnerships” where “trust” was important (I) and suppliers were also considered to be “customers” (VI, VIII). Regarding transactional relationships, digital interfaces with suppliers may not amortise the necessary efforts and costs (VI), so the question was raised whether “more digitalisation” was desirable for all suppliers (III). Regarding partnerships, two interview partners were positive about the enhancement and intensification of relationships through digitalisation (IV, VIII). In these cases, entire products may be produced for the buying firms, and innovation may be carried out together with suppliers (V).

Among the more advanced digital technologies used in buying firms, there are databases for supplier data following different approaches to optimise “source-to-contract” procurement processes and “purchase-to-pay” integration (i.e. electronic supplier integration) (VI). The company used both “classical EDI” and “web-EDI”, offering different platforms with different levels of sophistication for varying types of orders (e.g., paper supply vs. more complex parts) (VI). Some platforms can be used for free by the suppliers, while other more sophisticated platforms, e.g., to exchange design plans, have to be paid for by the supplier (VI). Suppliers additionally frequently referred to the use of commercial cloud services (A, C, E, F) (depending on the confidentiality agreements (A, F)), and the use of “WeChat” or “QQ” (both instant messaging software services owned by the Chinese firm Tencent) for non-confidential data. In the case of confidential data, “offline” USB flash drives or paper-based data exchange were reported to be used for data safety reasons (A, H).

Asked about the use of BDA and AI, limited uptake of BDA and AI solutions in SCC was reported by the interviewed firms. BDA (and sometimes AI) was mentioned as a means used, e.g., in marketing (E), (predicting) market trends (I, B, C), screening the competitive situation (A), understanding the use of companies’ products by customers (A), and quality management (I, B), but to a lesser extent in direct collaboration with the supplier. One such example was the analysis of output fluctuation at the suppliers’ plants. BDA was used to suggest correlations between variations in outputs and other indicators, such as the level of experience of employees working at a machine (I). However, two reasons for low uptake of BDA and even lower uptake of AI reported by firms was the lack of a unified understanding of what BDA and AI actually are (I, D) and, in the case of suppliers, a lack of internal capacity to conduct BDA and use AI techniques (C, D, F, G) was mentioned. Table 9 provides a summary of technologies the interview partners reported using for each digital maturity category.

Digital maturity	**low**	**Intermediate**	**high**
Technologies	Email (II, III, VII, IX, X, A, B, C, D, E, F, G, H), excel tables (I, II, III, VIII, IX, X IV, V, B, C, D, E, G), videotelephony (VII)	ERP (II, III, IV, VI), purchase-to-pay integration, (web-)EDI (II, IV, VI), “WeChat” or “QQ” (both instant messaging software services by Chinese firm Tencent) (A), cloud services (A, C, E, F)	Big data analytics (I, II, A, B, C, E), AI (V, A), IoT (I, F), blockchain (VI)

Table 9: Digital technologies used in the interviewed firms in SCC.

3.4.2 Opportunities, risks, and obstacles related to digitalisation for sustainable SCC

3.4.2.1 Perceived opportunities for environmental upgrading but few implemented use cases

Buying firms and suppliers alike expected several opportunities for sustainable SCC to arise from digitalisation. For a high number and variety of suppliers, data management could be improved by digitalisation in the future (X). Moreover, firms expected to be able to measure how energy is used in collaborating firms and which efficiency measures are in place (I, II, VI, E, F). In a few cases, energy data were already analysed for and together with the supplier to detect savings potentials (I, II). Several interview partners suggested opportunities for digital technologies to enable better collaboration on material circularity in the supply chain (II, VIII, IX, B, C, G). Digitalisation was expected to enable tracking of resources (IX, VIII, B, G), predicting sustainability risks for suppliers in the supply chain through big data analysis (V) and machine learning (VI), and reducing paper-based communication (VI, F). One buying firm, for instance, reported the development of a blockchain to track and trace emission data (VI) and others reported placing great hopes on blockchain technology for transparency (VIII, IX).

Our quantitative question regarding the effect of digitalisation in sustainable SCC on environmental upgrading (see Table 10) supports our impression that firms perceived potential created through digitalisation for more environmental sustainability in the supply chain. When asked about the effect of digitalisation on firms' capacity to create environmentally friendly innovation, both buying firms and suppliers expected a moderately positive effect (3.8 and 3.3, respectively, out of 5). The influence of digital technologies on the transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes was assessed even more positively by suppliers than by buying firms (4.2 and 3.6, respectively), indicating that firms expect a facilitation of "green" knowledge transfer through digitalisation.

	Buying firms	**Suppliers**
Green innovative ability	3.8 (N = 9)	3.3 (N = 8)
Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes	3.6 (N = 9)	4.2 (N = 8)

Table 10: Assessment of the influence of digitalisation in sustainable SCC on two environmental upgrading indicators. Note: Scale ranges from -5 (very negative influence) to +5 (very positive influence); one buying firm interview participant did not answer the above assessment questions.

Generally, however, sustainability concerns played a subordinate role as a determinant, or driver, of digitalisation in SCC in all our interviews. While general statements about the positive (economic) effects of digitalisation for SCC were common, e.g., regarding BDA and AI to enhance the logistics efficiency of multiple sources and materials (D) or the synchronisation of supply and demand (I), few interview partners pointed out specific sustainability purposes of digitalisation. Currently, buying firms often request that suppliers provide certificates about meeting specific regulations but do not manually or digitally verify this information, e.g., by collecting real-time data on energy efficiency and use at collaborating firms. Granular sustainability information (beyond certificates) is reported to be less relevant and difficult to obtain at the moment (III, IV, V, VI, VII, VIII). Thus, at the time of the interviews only few firms had already realised some of the expected sustainability opportunities of digitalisation, and none of them had implemented system-wide Industry 4.0 solutions for this purpose. However, there were a few implemented use cases of digital technologies for sustainable SCC. A list of implemented and envisioned use cases of digital technologies for sustainable SCC can be found in Table 11.

	Environmental data gathering and analysis on platforms	**Managing energy use and environmentally optimising logistics chains**	**Improving material circularity**
Measure implemented in a specific case	Establishing firms' own data platforms to collaborate with suppliers (IV, VI) and to measure CO2 emissions along the supply chain (II) Predictive risk assessment through BDA: assessing parameters as to whether companies are at high risk of not meeting their sustainability targets, subsequent selective and risk-driven collaboration with suppliers (V)	Detecting savings potentials in suppliers' plants by measuring machine energy use data through sensors in the machines (IoT) (I) Using BDA to optimise truck fleet routes in logistics processes of buying firms and suppliers (I) Using IoT and BDA to reduce energy consumption in production lines, reported effect of reducing energy consumption per product unit by 3% compared to the previous year (F)	Tracking & tracing containers and reusable packaging material, reported to reduce the amount and cost of packaging (II)
Measure envisioned	Linking and analysing previously unrelated databases through BDA and machine learning in the company to identify supplier sustainability risks (V) Anticipating sustainability risks in the supply chain through BDA: Analysing data on companies that have signed a code of conduct over a time span of three to five years, suggesting correlations on whether firms from different regions face higher or lower risks of breaching sustainability regulations in the future; analysing the likeliness and effects of extreme weather events such as hurricanes in the supply chain (VI) Preventive maintenance of wind energy turbines through machine learning (VI)	Calculating Product Carbon Footprint along the chain (VI) Determining the closest location of production facilities to retailers, i.e. choosing where to produce according to expected buyer locations (I) Determining the use of data centres and servers according to where renewable energies are available (VIII) Optimising logistics chains (D, F)	Using digital imprint of material information to learn why a produced product had failed and improve product development processes accordingly (IX) Improving recycling collaboration supported by digital technologies, contributing to recycling of discarded appliances (B, C, G) Tracking and tracing of packaging material (C, G) Using big data analysis to gather recycling information of scrap products (B)

Table 11: Use cases of Industry 4.0 technologies for sustainable SCC identified by our interview partners.

3.4.2.2 Little awareness of environmental risks

Our analysis indicates that there are several blind spots in the interview partners' awareness of adverse direct and indirect effects of digitalisation in SCC. Direct effects comprise increased energy and material use through digital technology use. An indirect environmental risk can arise, when increases in efficiency (material, energy) create rebound effects (Kunkel and Tyfield 2021). Environmental risks of digitalisation in SCC were not mentioned frequently by our interview partners. Interview partners briefly touched upon the issues of material use of digital technologies, high return rates induced by digital ordering, increased use of batteries in the IoT, and disposal of products in the supply chain (II, VIII, IX, B, C, G). One supplier spoke of the high velocity of changes and customisation of products in the electronics sector, possibly leading to negative environmental effects (C). Moreover, one supplier recognised that environmental challenges in the supply chain and digitalisation were systemic challenges that can only be solved by including all supply chain partners (D).

3.4.2.3 Several obstacles to digitalisation for sustainable SCC

Several obstacles have been identified by our interview partners that currently hamper digitalisation for sustainable SCC. These obstacles are summarised in Table 12, structured along the dimensions "socio-technical", "economic", and "legal and political".

Socio-technical	**Technology and data availability**	No tool and no data available to calculate, e.g., emissions of delivery trucks in the entire logistics chain (VI)
	Engagement and role of suppliers	no habit of data collection among (second-, third-, ... tier) suppliers (A), especially on environmental and social indicators, e.g., no measurement of emission data by suppliers (VI)
	Lack of expertise in technology implementation	a lack of internal capacity to conduct BDA and use AI techniques (C, D, F, G)
Economic	**Internal resources in firms**	Insufficient resources to obtain sophisticated software for supplier management (III)
	(increasing) cost	insufficient resources to actively foster sustainability practices by suppliers, as this is labour-intensive and expensive (III) expectation of increasing costs of raw material used to produce digital technologies (VIII) and thus of an increasing need to use refurbished hardware (VIII)
Legal and political	**Weak regulations**	Dispersed social and environmental reporting landscape, no globally binding supply chain sustainability standards, suppliers report having few or no requirements for sustainability from the buying firms' side (A, G, H)
	Data confidentiality requirements and lack of trust in secure infrastructure	data confidentiality poses challenges to data sharing among firms, secure transmission channels might be lacking (VIII, F, G)

Table 12: Perceived obstacles to digitalisation for sustainable SCC.

3.5 Discussion: Managerial and policy levers to improve the socio-ecological performance of the supply chain through digitalisation

The aim of our study was to explore the current use of digital technologies in SCC, as well as the opportunities, risks, and obstacles related to digitalisation for sustainable SCC. In this section, first, we propose two hypotheses to explain our observations arising from the analysis. Second, we suggest three levers with which to improve the socio-ecological performance of the supply chain through digitalisation in sustainable SCC.

3.5.1 Hypothesis 1: Relationship between firms determines the degree of digitalisation in sustainable SCC – and the success of sustainable SCC

We inferred from our interviews that the relationship between firms in the supply chain seems to be an important influencing factor in digitalisation for sustainable SCC. Usually, supply chain firms are hesitant to share more information than needed (Voigt et al. 2019). This tendency is supported, e.g., by statements of concerns about data safety in our interviews. However, to harness the proposed opportunities for sustainability (section 3.4.2.1), extensive data collection and exchange by different supply chain actors is fundamental. Even if Industry 4.0 technologies were to be used, such as sensors measuring machine energy use and providing real-time energy use information (Liang et al. 2018), a compatible technological infrastructure and a high level of trust would probably be needed between firms to enable mutual access to this information by supply chain partners. In this regard, two large firms mentioned that they assess the digital maturity of suppliers with a handbook upon establishing the business relationship. However, if suppliers can be replaced easily, if the interaction with a higher number of suppliers through digitalisation becomes feasible (VI), and thus there is less potential for a long-term partnership, then firms might be less likely to engage in their partners' (digital) internal processes and environmental data management, and instead switch to another supplier if any sustainability issues arise or sustainability targets are not met.

While in our interviews, suppliers did not report technological barriers to collaboration with buying firms, there is a risk that powerful firms (be it buying firms or suppliers) in the supply chain when advancing Industry 4.0 technologies solutions, even for sustainable SCC, force less powerful firms to implement compatible hardware and software systems and provide data, while not necessarily obtaining useful data themselves. This might happen, for instance, if sustainability platforms are exclusively managed by a small number of powerful firms, or if digitalisation solutions are too advanced for a specific country context (Luthra et al. 2020; Ozkan-Ozen, Kazancoglu and Mangla 2020).

3.5.2 Hypothesis 2: Digitalisation and sustainability management are not linked in firms

In our interviews, we gained the impression that especially large firms have achieved maturity in using digital technologies for business-related functions in SCC, such as order transmission between companies. However, little collaboration on environmental sustainability-related topics using the companies' digital technologies in the supply chain was reported by our interview partners — an observation that is supported by the focus of applying Industry 4.0 technologies for economic rather than environmental benefits (Margherita and Braccini 2020). The use of Industry 4.0 technologies for sustainable SCC in the interviewed firms did not appear to be widespread, as showcased by the low adoption of BDA and AI solutions for sustainable SCC. Some implemented examples of advanced technology use mentioned by our interview partners include online collaboration platforms, predictive analyses of sustainability risks with suppliers, and optimisation of truck routes. We conclude that either there is little existing sustainable SCC realised through the main digital information and communication systems used in supply chain management by the firms we interviewed, or else sustainability collaboration is detached from the broader supply chain management in the company and therefore beyond our interview partners' awareness. In support of the latter notion, earlier research has already identified the problem of "enterprise information islands" regarding sustainability data (Tao et al. 2014). Moreover, we were rarely able to identify an expert on both sustainability and digitalisation in supply chain management in any company, possibly indicating a lack of awareness and expertise at this intersection.

3.5.3 Managerial and policy levers to improve the socio-ecological performance of the supply chain through digitalisation

We structure the suggested measures around three levers: socio-technical, economic, and legal & political measures (Table 13).

Goal: Overall improved socio-ecological performance of the supply chain		
Managerial and policy levers		
Socio-technical	**Economic**	**Legal & Political**
Use digital technologies adapted to diverse firms' (country) contexts to enable 'digital environmental upgrading'	Explore economic-environmental win-win situations to amortise investments in digitalisation for sustainable SCC	Create open, secure, and conducive environments for gathering, sharing, and analysing sustainability data

Table 13: Levers for more socio-ecologically sustainable supply chains.

From a socio-technical point of view, support structures from more digitally mature companies, governments, and/or non-firm actors for less digitally mature firms are needed that create possibilities for "digital environmental upgrading" for firms. **Digital environmental upgrading** means a continuing digital innovation process where socio-technical knowledge regarding digitalisation is co-produced and applied among supply chain parties to achieve environmental goals. Cheap and context-dependant, (possibly low-tech) solutions to collaboration between supply chain partners should be explored, especially further upstream, in order to overcome the problem of proposing ever more technologically sophisticated technologies that fail due to organisational, financial, and other non-technological problems across the supply chain (Luthra et al. 2020; Yadav et al. 2020b). Sustainability indicator performance will need to be measured along the supply chain in order to critically assess the effectiveness of any Industry 4.0 measure towards more sustainable supply chains. In this regard, a combination of several technologies could create synergies. For instance, a blockchain-based information storage in trustworthy, public cloud infrastructures (such as proposed by the GAIA-X project), could enable the more independent evaluation of environmental parameters along the supply chain, with the aid of algorithms developed collaboratively among supply chain partners. Collaboration with non-firm actors in the supply chain, e.g., government agencies, sectoral business associations, specialised service companies, or utility providers, could facilitate this task. Several initiatives and solutions work at this nexus, such as the private sector initiatives "Global e-Sustainability Initiative (GeSI)", the Responsible Business Alliance (RBA), and service providers such as "Sustainabill" or "CircularTree".

From an economic point of view, firms should aim to create economic and environmental win-win situations. Taking the examples of using Industry 4.0 technologies in supplier collaboration on energy, material use and waste, we concur that the interviewed firms did not yet fully take advantage of the existing and anticipated possibilities of digitalisation for such win-win situations in sustainable SCC (Dev, Shankar and Qaiser 2020). For instance, one supplier expected logistics platforms supported by BDA and artificial intelligence to solve the problem of the complexity of supplier evaluations (D) but did not yet take sustainability parameters in supplier evaluation into account. However, choosing suppliers with advanced energy management systems might enable the identification of energy savings potential and associated cost reduction in the future. Furthermore, data analysis to make the sampling of suppliers for audits on sustainability more efficient and effective (VI), could also help to reduce the costs of such audits – a potential that is not yet widely exploited.

We argue that firms' approaches to energy use reduction and material circularity could be incorporated as an additional selection criterion in the selection of collaborating firms, including upstream suppliers beyond the first tier. This is important, as suppliers further upstream run an even greater risk of not meeting sustainability standards (Villena and Gioia 2018). To this end, organisational and strategic priorities should be shifted towards sustainability, e.g., by employing a digital sustainability expert who explores the potential of digitalisation for sustainable SCC and its economic benefits. This could also help to amortise investments associated with digitalisation in sustainable SCC.

From a legal and political point of view, policy makers should create both constraining and enabling legal environments within which companies have a clear mandate to create sustainable supply chains. On the enabling side, secure legal frameworks for gathering, sharing, and analysing sustainability data have to be created by addressing Intellectual Property and data safety concerns and incentivising collaboration across the supply chain. National (industrial) policies should incentivise the adoption of digital sustainable SCC between buying firms and suppliers. Public funding should be dedicated to public digital infrastructure, such as secure cloud services, and digital environmental innovation in the supply chain, that meets the conditions for wide-spread adoption in upstream countries and contributes to environmental upgrading along the supply chain in the Global South (Marchi, Maria and Micelli 2013).

On the constraining side, supply chain-wide governance measures, such as carbon pricing and circular economy approaches aimed at environmental sufficiency and questioning (solely) efficiency-enhancing digitalisation measures, could help to prevent digital rebound effects (Kunkel and Tyfield 2021). In the case of optimising truck routes through BDA, for instance, more efficient logistics routes may increase the total amount of logistical operations as the price of truck transport decreases (becoming more efficient and driving less unnecessary miles). Such rebound effects in transport have been documented in the literature (Hymel, Small and Van Dender 2010; Jamasb and Llorca 2021). More generally, when a firm can materialise cost savings using BDA, it is also likely to be more competitive vis-a‘-vis other firms in the market and offer services and products at cheaper prices. If demand is elastic, this can entail more demand for a service or product and increase its use or production volume. Eventually, digitalisation-related efficiency gains might be overcompensated by the scale effect (rise in overall use/production). Thus, containing rebound effects in the face of digitalisation, is a necessary condition for any digitalisation measure to contribute to sustainability.

3.6 Limitations

Our study suffers several limitations. We aimed to reach high-level employees responsible for electronics companies’ supply chains in a period of global uncertainty and supply chain distress. Consequently, we were not able to interview a representative number of interview partners from buying firms and suppliers, which hampered the external validity of our study. The small number of participants and our convenience sampling approach did not allow us to derive statistically verifiable results. Our results should therefore be viewed as indications for phenomena that have yet to be further validated in future studies, including for other sets of companies and in other geographical contexts. However, we consider the exploratory approach of the study to be an interesting way to touch upon a variety of digitalisation topics and draw links between research and practice. We are able to provide insights into the otherwise largely obscure firm-internal initiatives and expectations regarding digitalisation for sustainable SCC.

Another limitation of interview studies like ours is that interview partners might be biased, or have had incentives to answer in socially desired ways, not wanting to expose possible deficiencies in their companies, e.g., with regard to digital maturity or sustainability. One attempt to validate our findings to some extent was to include two perspectives on SCC, i.e. both buying firms’ and Chinese suppliers’ perspectives, and match buyers’ and suppliers’ questions, as well as to employ a theory-driven qualitative analysis approach (Yin 2003). Because buyers and suppliers were randomly chosen without having a direct business relationship with one another and because interviewees remained anonymous, there was little risk of firms answering in socially desirable ways in an attempt to maintain old or attract new business contacts. However, this is also why it is not possible to derive conclusions as to the specific relationships between the interviewed buying firms and their suppliers in the analysed regions or countries.

To reduce the impact of researcher bias and increase the comprehensibility of our interview questions, we performed a pre-test of our interview guideline with an industry practitioner in the field of supply chain and information systems, who gave us an external perspective on the interview questions we chose and the interview process. As a consequence, we adapted the formulation of the interview questions to our target group of supply chain experts, avoiding using conceptual terms such as “Industry 4.0”, “cyberphysical systems” or “connectivity” in our interviews and choosing in our view more practically relevant terms in the field of SCC related to Industry 4.0. Nonetheless, other sources of subjectivity remain in the interviewing and qualitative content analysis. For instance, despite attempts to increase reliability, coding remains a subjective process. There is always leeway in the interpretation of interview partners’ statements and in categorising them. We tried to reduce this bias by working together among two coders in this study, discussing with colleagues working in the field, and drawing from theory and prior empirical studies for the establishment of our category system. Agreement amongst researches can increase reliability of the coding scheme and the data analysis (Carter and Easton 2011).

Lastly, in the Chinese supplier data, we chose to conduct written interviews and had to translate Chinese to English and vice versa. Therefore, cross-cultural and language barriers may have influenced the results from our analysis of the Chinese interviews. However, with the support of a native speaker of Chinese who reviewed the translations, we were able to identify and eliminate some of the uncertainties around interviewees' responses and thus counter such issues.

3.7 Concluding remarks: Some suggestions on fostering Industry 4.0 *for* sustainable supply chains

While digitalisation, and Industry 4.0 in particular, offers opportunities for sustainable SCC and environmental upgrading, it is not a sufficient condition for sustainability along the supply chain. Socio-technical, economic, legal, and political hurdles also have to be overcome (Luthra et al. 2020). We posed two research questions. First, how are digital technologies currently used in SCC? Second, what are the opportunities, risks, and obstacles related to the use of digital technologies for sustainable SCC?

Our results indicate that a broad range of basic digital technologies are used in SCC, with fewer cases of advanced Industry 4.0 technologies' application. However, most of the digital technologies in SCC mentioned by our interview partners were not focused on sustainability-related applications. Digital technologies are mainly envisioned to enable a more frictionless supply chain, e.g., BDA for synchronising supply and demand between firms and analysing (future) customer preferences. Sometimes digital technologies were reported to offer additional sustainability use cases, e.g., reducing energy consumption in production lines by using Internet-of-Things technologies. With regard to the opportunities, risks, and obstacles of digitalisation for sustainable SCC, digitalisation was generally viewed as positive for economic and environmental sustainability by most firms we interviewed, e.g., through its potential to induce energy efficiency gains, and only a few risks, such as increasing resource demand, were mentioned. However, several hurdles, including socio-technical, economic, and legal and political ones, need to be addressed in order to harness the potential of digitalisation for sustainable SCC.

We therefore argued for a targeted effort by industry and policy makers to foster (existing) digitalisation initiatives along the supply chain for sustainable SCC in an inclusive way to achieve high uptake and gains, particularly among suppliers globally along the supply chain, as showcased by the example of China. We suggested three levers for business and policy makers to improve the overall socio-ecological performance of supply chains through digitalisation: using digital technology adapted to diverse firms' (country) contexts, exploring economic-environmental win-win situations for digitalisation in sustainable SCC, and creating secure legal frameworks for gathering, sharing, and analysing sustainability data. The ultimate goal of any such measure should be an *overall improved socio-ecological performance of the supply chain.*

Despite several limitations of our qualitative, exploratory study, such as limited generalisability, we believe that insights from this study contribute to link the intertwined, but often separated research fields of sustainable supply chain management, global value chains, and digitalisation/Industry 4.0 in order to understand digitalisation from the perspective of collaboration along the supply chain. From a practical point of view, this study enabled us to suggest policy and managerial levers taking into account firm, supply chain, and governance aspects of sustainable SCC. These levers can give hints to policy makers and managers on how to create framework conditions that enable sustainable SCC and (digital) environmental upgrading. From a research point of view, our study yielded indications at the intersection of these research fields that build a basis for future research.

Specifically, the issue of how digitalisation enables sustainability learning in (electronics) value chains deserves more research attention. First, it will be helpful to investigate how sharing environmental data, knowledge, and innovation along the supply chain can be improved despite existing concerns about intellectual property sharing amongst firms. Studies could investigate, e.g., how existing technology transfer licences could be adapted to privilege “green innovation” or include sustainability requirements. Second, it will be insightful to scrutinize more in-depth first-tier suppliers and collaboration with further upstream suppliers, also from a broader range of countries. For instance, large suppliers were suggested to sometimes have a stronger leverage for sustainability vis-a‘-vis small buyers than the other way round. It will be interesting to learn more about first-tier suppliers’ own motivation and ability to achieve (digital) sustainability innovation, and how they could contribute to fostering environmental upgrading along the supply chain. Likewise, researchers can engage with second-tier, third tier, and further upstream suppliers about their perception of the opportunities and risks of sustainability in the supply chain through digitalisation. Doing so would also enable us to draw parallels and find distinctions between the specific Chinese context and other low- and middle-income country contexts. For instance, in the discussion around its integration into electronics supply chains, Vietnam has managed to attract production capacities (World Bank 2020), while high logistics costs due to their distance from Asian production hubs make it difficult for African countries to participate in electronics value chains. An intriguing question for future research would be to investigate whether digital technologies have any effect on these geographical differences and what this would mean for (environmental) sustainability.

Sustainability and digitalisation in supply chains are two complex transformation processes. In light of the European “green and digital twin transitions”, commitments to carbon neutrality in the EU and China within decades, and existing trade relationships, it will become ever more important to govern both digitalisation and sustainability across borders going forward. This will likely require immediate intervention and long-run strategic planning of policy makers, civil society, academia, and companies. To deal with the challenges and dilemmas that arise, solutions should be developed through a broad, science-based dialogue with all relevant stakeholder groups, orientated by the normative goal of enhancing the socio-ecological performance of supply chains. If guided by sustainability values, digitalisation can certainly help to achieve this goal.

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CRediT authorship contribution statement

Stefanie Kunkel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Marcel Matthess**: Conceptualization, Data curation, Investigation, Writing – review & editing. **Bing Xue**: Resources, Validation. **Grischa Beier**: Supervision, Validation, Writing – review & editing.

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Appendix

Appendix A: Interview Guidelines

Interview guideline development

The interview guideline was developed in a theory-driven, collaborative process starting in April 2020 including several rounds of internal group revision. In order to ensure validity, we performed a pre-test of the guideline in July 2020 by conducting an interview with an industry expert. The pre-test led to some adjustments, accounting especially for the feedback that, according to the expert, the desired information and knowledge was likely to be spread out among various experts and that we would need to tailor our guideline more towards the target group of supply chain managers (in opposition to, e.g., IT or sustainability experts). We also discussed and revised the guideline together with colleagues working in the field and drew from prior studies that chose similar approaches in order to increase validity (Busse et al. 2016).

Interview guideline (buying firms)

1. Please describe your position in the company and your responsibilities and your disciplinary background.
2. What do your supply chain (SC) processes look like regarding procurement (and reverse logistics) and cooperation with suppliers?
    - How do you proceed in terms of:
        - Identification of suppliers
        - Choice of suppliers
        - Other collaborative processes with supplying companies
    - Can you tell us what current challenges you are facing with regard to these processes?
3. How many suppliers does your company have, and how are they geographically distributed?
4. Estimate / Please rate: How important are the following aspects to you regarding the suppliers' performance on a scale from 1 to 10, 1 being not important at all, 10 being very important?
    - Transparency
    - Price
    - Quality
    - Compliance with scheduled delivery dates
    - Recommendation from other partners
    - Digital equipment and know-how
    - Willingness to exchange data on the part of the suppliers for their integration into the supply chain
5. What data do you collect in the course of procurement?

  - What data do you collect on environment and social indicators?
  - Is there also a mutual exchange of data between your suppliers and your company?

6. Which tools do you use in detail for the collection and assessment of data (Excel, e-mail, ERP, EDI, others…)?
    - Do you use any specific tools for the storage and analysis of data on social and environmental indicators?

7. What are obstacles in the collection and assessment of data?
    - Are there any specific obstacles when it comes to the collection and assessment of data on social and environmental indicators?

8. Do you already use big data analytics (and artificial intelligence) to generate information about your suppliers? If so, for what purposes?
    - Just to clarify: We view big data analytics as a technical means to gather and analyse large amounts of unstructured and heterogeneous data.

9. If not: Do you already use big data analytics in other SC processes?

10. Can you imagine using (other) digital technologies in SC management in the future?
    - For instance, can you think of instances in which algorithms could optimise decision-making processes? Are there cases in which tools that are able to give meaning to existing data would assist your work?

11. Which economic, ecological, and social effects of the use of digital technologies do you observe or do you expect to observe in the future in your company or your suppliers?

12. Estimate: How will the use of digital technologies influence the below aspects? Please rate on a scale from -5 to 5 (-5 probably very negatively, 0 probably neutral, 5 probably very positive).
    - Exchange of data on the environment and social issues (transparency)
    - Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes
    - “Green“ innovative ability
    - Compliance with legal and voluntary reporting standards on environmental and social aspects
    - Involvement of (new) suppliers in the value chain
    - Employment and wages in supplier companies

13. Imagine you could reinvent the existing SC processes in the area of sourcing (and possibly reverse logistics): Which processes would have to change and which tools and technologies would be needed to make processes more ecologically and socially beneficial?

Interview guideline (suppliers, translated into Mandarin))

1. Welcome, thank you for your willingness to participate, reminder of the goals of the study, permission to record?
   1. 欢迎，感谢您的参与，提醒您此次研究目的，是否允许会议记录?

2. Please describe your position in the company, your responsibilities, your age, and your disciplinary background, and particularities of supply chain management in the electronics branch.
   2. 请描述您在公司的职位，您的职责，您的年龄以及学术背景，电子行业供应链管理的特性

3. How many branded firms does your company supply, and how are they geographically distributed?
   3. 贵公司共供应多少品牌公司? 他们的地理分布是怎样的?

4. How many suppliers does your company have, and how are they geographically distributed?
   4. 贵公司有多少的供应商? 他们的地理分布是怎样的?

5. What do your supply chain (SC) processes look like regarding cooperation with both branded firms/OEMs and your suppliers?
   5. 对于品牌公司/原始设备制造商与贵公司供应商之间的合作，您的供应链流程是怎样的?

6. Please rate each on a scale from 1 to 10: How much do the branded firms that you supply value the following aspects in you:
   6. 请按 1 至 10 比例评分：您供应的品牌公司在以下方面对您是怎样评估的?

   - Transparency 透明度
   - Data availability 数据可用性
   - Price 价格
   - Quality 质量
   - Sticks to delivery dates 确保交货日期
   - Recommendation from another firm 其他公司推荐
   - Digital equipment and know-how 数字化设备及专业技能
   - Willingness to exchange data 交换数据的意愿

7. What data do branded firms demand from you, including about environmental and social indicators?
   7. 品牌公司需要您提供哪些数据? 包括环境及社会指标?

8. What data do you demand from your suppliers?
   8. 您需要从供应商那里得到哪些数据?

   - Do you also collect data on environmental and social indicators?
     您也需要收集环境及社会指标数据吗?

9. Which tools do you use in detail for the collection, transmission, and assessment of data (pencil & paper, excel, e-mail, ERP, EDI, others...)?
   9. 您在收集，传输及评估数据时使用了哪些工具？（铅笔和纸张，excel, 电子邮件，ERP, EDI, 或其他. . . ）

   - If you collect data on environmental and social indicators: Which tools do you use for that?
     如您收集了环境及社会指标数据：您**使用到了哪些**工具?

10. What are obstacles in the collection and assessment of data?
    10. 在收集及评估数据方面有哪些障碍?

    - What are specific obstacles around data on environmental and social indicators?
      在收集环境及社会指标数据时**有哪些具体障碍**?

11. Do you already use big data analytics and/or artificial intelligence in the cooperation with branded firms? If so, for what purposes? Descriptive or prescriptive? Also for ecological or social purposes?
    11. 在与品牌公司合作时您是否已经运用到了大数据分析和/或人工智能? 如果是，您的目的是? 描述性还是规定性? 为了生态还是社会目的?

12. If not: Do you already use big data analytics in other SC processes?
    12. 如果没有：您是否已经在其他供应链流程中使用到大数据分析?

13. If not: Can you imagine using specific digital technologies in SC management in the future?
    13. 如果没有：您能想象在未来的供应链管理中会使用到的特定的数字技术吗?

    - E.g. Do you use other tools to assess large amounts of unstructured data? 例如：您使用过其他工具来评估大量的非结构化数据吗?
    - Do you use algorithms to optimise decision processes? 您使用过算法来优化决策过程吗?

14. Which ecological and social effects of the use of digital technologies do you observe or do you expect to observe in the future in your company/ at the branded firms that you supply, e.g. with respect to energy use, resource use or wages in your company?
    14. 您在贵公司/供应的品牌公司中观察或未来期望观察到哪些使用数字技术的的生态和社会影响? 例如：能源的运用，资源运用或公司工资方面?

15. Estimate: How will the use of digital technologies influence the below aspects? Please rate on a scale from -5 to 5 (-5 probably very negatively, 0 probably neutral, 5 probably very positively). 15. 请预估：数字技术的使用会怎样对以下几个方面产生影响? 请按-5至5分段评分（-5 可能非常消极，0 可能中立，5 可能非常积极）。

    - Exchange of data on the environment and social issues 环境和社会问题的数据交换
    - Transfer of knowledge about the use of energy- and resource-efficient manufacturing technologies and processes **关于能源及**资源高效制造技术和过程的知识转换
      - In your company 对**您公司**

  - At your suppliers 对您的供应商
- “Green“ innovative ability “绿色”创新能力
  - In your company 对您公司
  - At your suppliers 对您的供应商
- Compliance with legal and voluntary reporting standards on environmental and social aspects 遵守环境和社会方面法律及自愿报告标准
  - In your company 对您公司
  - At your suppliers 对您的供应商
- Involvement and realised gains of your own company in the supply chain 您自己公司在供应链中的参与及收获
- Involvement of (new) suppliers in the value chain （新）供应商在价值链中的参与度
- Employment and wages in your own company 贵公司的工作及薪资
- Employment and wages at your suppliers 您的供应商的工作及薪资

16. Imagine you could reinvent the existing SC processes in the area of sourcing: Which processes would have to change and which tools and technologies would be needed to make processes more ecologically and socially beneficial?
16. 设想一下您能在采购中重新设计现有的供应链过程：哪个过程是必须改变的？哪些工具及技术会使整个流程更具生态及社会效益?

17. Optional: What are your current challenges in supply chain management?
17. 可选：您目前在供应链管理方面面临的挑战是什么?

18. Are there any other aspects that we haven’t mentioned yet but which you would like to add because you think they are important?
18. 有没有其他方面我们没有提及，但您认为较重要并愿意补充?

19. Do you have contacts who might be willing to talk to us and share their expertise?
19. 您有愿意与我们交流并分享他们专业知识的联系人吗?

Appendix B: Statistics about buying firms and suppliers

Interviewee (Position)	**Size of firm**	**No. of suppliers**	**Location of suppliers**	**Sub-sector / product type**
I (Director Advanced Manufacturing)	Large	approx. 30 000	Globally distributed (approx. 60 countries)	Multimedia, Automotive electronics
II (Smart Logistics Manager)	Large	"10000s"	Globally distributed with clusters in Europe, Asia (China), North America	Smart home & household appliances
III (Supply Chain Manager)	small/ medium	approx. 25	10 biggest ones in Asia, 10–15 in Europe	Consumer electronics peripherals
IV (Director Supply Chain Management)	Large	–	Concentrated in Germany; China, Romania, US, Mexico	Electrical connectors
V (Director Supplier Sustainability)	Large	4500	33% Asia (majority in China), 33% in Americas (mostly North America), remaining Europe clustered around Poland, the Netherlands, and Germany	Household appliances, multimedia
VI (Procurement Manager)	Large	–	–	Household appliances
VII (Supply Chain Manager)	Large	–	Concentrated in China, significantly smaller in India, Vietnam, local services from Switzerland	Telecommunication equipment
VIII (Procurement & Manufacturing Manager)	small/ medium	100–150	Concentrated in Germany, smaller clusters in China	Data centre equipment
IX (Business Development Manager)	–	50–100	Concentrated in Germany, rest of Europe	Smart sensors
X (Sustainable Sourcing Manager)	Large	>20,000	Clustered around Asia for hardware and components, services all around the world	Multimedia, mobile phone

Table 14: Statistics about buying firms and suppliers. Note: "Size of firm" is defined in our paper according to the number of employees: small/medium (1–500 employees), large (501–500,000 employees); "-" indicate gaps in information; in the first column, where two positions are mentioned, two persons were interviewed.

Interviewee (Position)	**Production location**	**Size of firm***	**No. and location of customers (brand firms)**	**No. and location of customers (brand firms)**	**Sub-sector/ product type**
A (Supply Chain Manager)	Shanghai	small/ medium	approx. 3,000 – 4,000 customers, largely SMEs and a few brand-name companies. High concentration in China, Taiwan, Hong Kong, few customers in Japan and the EU.	approx. 50 suppliers, mainly from Europe, US, Japan, Taiwan, China	Unspecified intermediate components
B (Production Director)	Suzhou	large	Unspecified customer base and location	Unspecified (large) and global supply base, concentrated in China	Laptops
C (Procurement Manager)	Nanjing	large	approx. 100 customers, mainly located in Europe, America, and Southeast Asia	approx. 320 suppliers, unspecified location	Household appliances
D (Production & Planning Manager)	Shenyang	large	approx. 70 customers, largely located in China, Latin America	approx. 100 suppliers, largely located in China, Europe, US	Smart measurement tools
E (Supply Chain Director)	Shanghai	large	Unspecified customer base, concentration in China	approx. 100 suppliers, concentrated in China	Household appliances
F (Production Manager)	Guangdong	large	approx. 200 customers, concentrated in SE Asia, India, the Middle East, North America, China	approx. 200 suppliers, concentrated in China, Japan, South Korea, US, Germany	Air conditioners
G (CEO)	Shenzhen	large	approx. 100 customers, all located in China	approx. 20 suppliers, concentrated in China	Unspecified intermediate components
H (Production Line Development Manager)	Taizhou	large	approx. 40 customers, concentrated in China	approx. 10 suppliers, concentrated in China	Unspecified intermediate components

Table 15: Statistics about suppliers. Note: "Size of firm" is defined in our paper according to the number of employees: small/medium (1-500 employees), large (501-500,000 employees); "-" indicate gaps in information; in the first column, where two positions are mentioned, two persons were interviewed.

Appendix C: Category system for the qualitative content analysis

List of codes that were developed in the collaborative coding process

1. Interviewee information
2. Information on electronics supply chain
3. Supply Chain Collaboration processes
    (a) Identification of suppliers

   (b) Choice of suppliers
   (c) Collaboration with suppliers

4. Data exchange and analysis
5. Digital tools & technologies
   (a) BDA & AI
6. Supplier collaboration use cases
7. Supply chain use cases
8. Sustainability implications
   (a) Supply Chain Collaboration sustainability conception
   (b) Observed impacts of digitalisation in SC Collaboration
      i. Economic
      ii. Environmental
      iii. Social
   (c) Envisioned impacts of digitalisation in SC Collaboration
      i. Economic
      ii. Environmental
      iii. Social
9. Obstacles to digitalisation
10. Opportunities & risks of digitalisation in sustainable Supply Chain Collaboration
   (a) Opportunities
   (b) Risks

Appendix D: From category system to research results

After the coding and discussing the researchers' codes, we reviewed all interview fragments that a) reported on the digital technologies that are used in the SCC of the respective firms, and b) linked digital technology use in collaboration to environmental sustainability, according to our research questions. We sorted digital technologies according to our digital maturity scheme. All reported digital technologies used in collaboration were accordingly reported in section 3.4.1.

With regard to the link between digital technology use in collaboration and sustainability, we differentiated between observed and envisioned impacts, as well as the triple bottom line of sustainability categories – social, economic, and environmental – to get an overview of all the sustainability aspects mentioned. Since this analysis focuses on the environmental dimension, we concentrated on the mentioned environmental aspects to further differentiate between "opportunities" and "risks" in these interview fragments. We report these in section 3.4.2. We further added opportunities and risks that emerged as a combination of the way firms collaborated digitally (research question 1) and the way they reported currently handling sustainability (mentioned during the interview).

We report the use cases in section 3.4.2 merged by clustering the reported sustainability applications of digital technologies along three specific environmental sustainability aspects in the supply chain, namely: environmental data gathering and analysis, energy use, and materials and waste in the supply chain. Our approach aims at including all information that is relevant to either research question 1 or 2 without discriminating against any information, in order to achieve our goal of obtaining a broad scope of digitalisation for sustainable SCC in the interviewed electronics firms.

In order to improve the validity of our findings, we conducted an additional interview with the representative of an electronics association who was responsible for increasing sustainability in the sector by using digital technologies. This interview was not used in the results section but helped to validate our coding decisions and identified foci for the results and discussion (Potter and Levine-Donnerstein 1999).

4

Industry 4.0 and energy in manufacturing sectors in China

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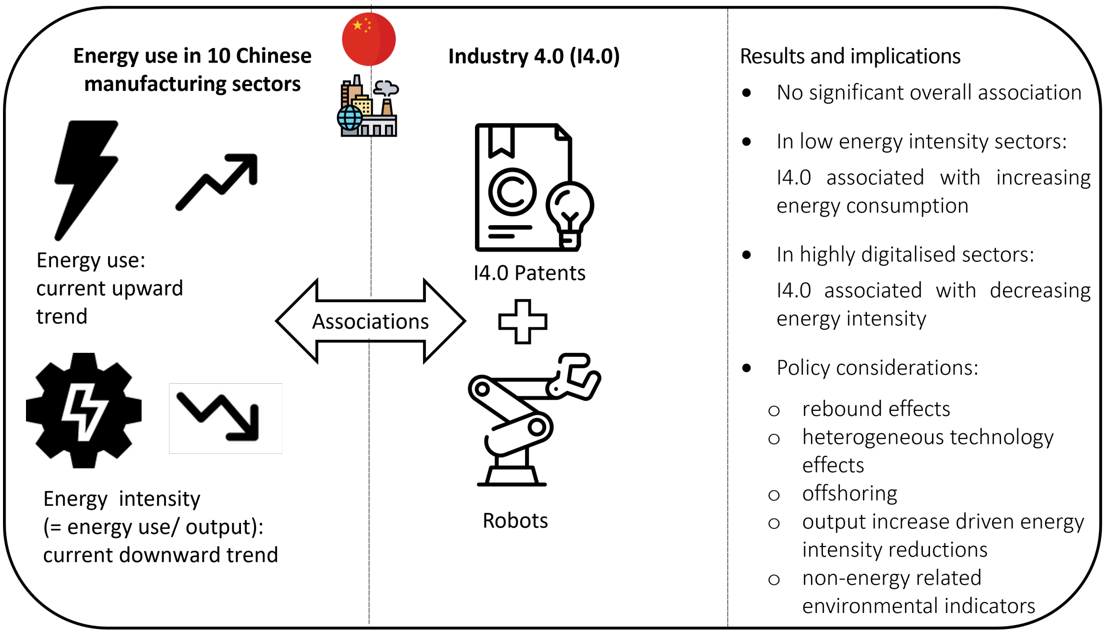
Abstract

Digitalisation in manufacturing (or “industry 4.0”) is expected to improve energy efficiency and thus reduce energy intensity in manufacturing, but studies show that it may also increase energy consumption. In this article, we investigate to what extent the degree of industry 4.0 is linked to energy consumption and energy intensity in ten Chinese manufacturing sectors between 2006 and 2019. We approximate the degree of industry 4.0 by combining data on a) patent intensity of industry 4.0-related technologies and b) industrial robot intensity. Our results indicate that there is no significant overall relationship between the degree of industry 4.0 and energy consumption or energy intensity, in contrast to some earlier studies in the Chinese context which find significant energy intensity reducing effects of digitalisation. We argue that industry 4.0 in China might have fewer energy related benefits than expected by politics and industry. Growth-inducing effects and outsourcing of energy-intensive manufacturing tasks, for instance, may counteract efficiency-related savings. To decarbonise manufacturing in line with China’s proclaimed objective of carbon neutrality by 2060, policy makers and industry should identify specific opportunities and take seriously the risks of industry 4.0. Focus should be on reducing absolute energy consumption as opposed to energy intensity which may disguise rebound effects; and the integration of renewable energies, particularly in the most energy-consuming sectors (metals, chemicals, non-metallic minerals). Digitally-aided flexibilisation of energy supply and demand in manufacturing may be one promising field of application for industry 4.0 to benefit sustainability.



Results and implications

- No significant overall association
- In low energy intensity sectors: I4.0 associated with increasing energy consumption
- In highly digitalised sectors: I4.0 associated with decreasing energy intensity
- Policy considerations:
  - rebound effects
  - heterogeneous technology effects
  - offshoring
  - output increase driven energy intensity reductions
  - non-energy related environmental indicators

Figure 10: Graphical Abstract, source: own elaboration using icons from Flaticon (undated[b])

Keywords

Digitalisation, Sustainability, China, Patent, Robot, Digital rebound

4.1 Introduction

The sustainability-related effects of digitalisation in industry[13], or industry 4.0 (I4.0), receive increasing attention in research, industry, and politics. I4.0 can be defined as the transformation of manufacturing organisations and human interactions within these organisations through digital technologies, with mutual dependencies between organisations, humans, and technologies in manufacturing systems (Beier et al. 2020c). There are expectations by industry and policy makers that I4.0 will not only create economic opportunities, but also positively impact sustainability of industry, e.g., through the provision of real-time environmental data along supply chains (Ghobakhloo 2020; Kunkel and Matthess 2020; Plattform Industrie 4.0 2019; Yadav et al. 2020a). China, being the largest manufacturer in the world with 30 % value added, increasingly frames I4.0 as a means to create economic growth while simultaneously helping to achieve energy saving goals, for instance, in the 14th 5-year-plan, Made in China 2025, the Internet+ action plan or in the white paper "Energy in China's New Era" (IEA/IRENA 2022; Sino-German Cooperation on Industrie 4.0 2021). Despite government-promoted energy intensity[14] reductions, however, Chinese manufacturing sectors' total energy consumption has increased in past decades (as shown in Figure 11 and 12). Given the industry sector's crucial role for the country's energy savings (Dong et al. 2018), the question arises how I4.0 will affect industrial energy consumption.

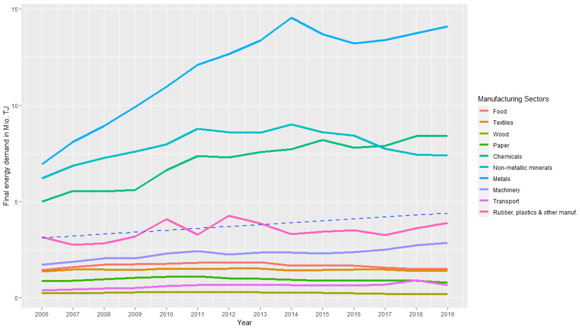


Figure 11: Energy use by manufacturing sector in China, 2006-2019

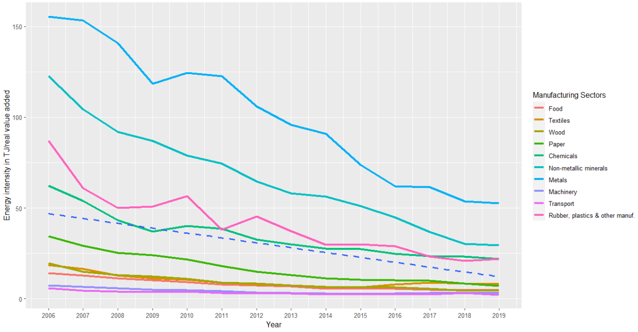


Figure 12: Energy intensity by manufacturing sector in China, 2006-2019

Empirical analyses of the effect of digitalisation and industry 4.0 on energy consumption and intensity, have shown mixed results (Wang and Xu 2021; Zhang and Wei 2022). Studies posit both energy consuming and energy saving effects of digitalisation (Husaini and Lean 2022; Lange, Pohl and Santarius 2020; Schulte, Welsch and Rexhäuser 2016) (see section 4.2). There are gaps in the literature, which further complicate the assessment of digitalisation's effects. Many studies analyse the broader effects of digital technologies on energy consumption (Salahuddin, Alam and Ozturk 2016; Schulte, Welsch and Rexhäuser 2016), but fewer do so in the Chinese context (Han et al. 2016; Wang, Wang and Han 2019; Wen, Lee and Song 2021; Zhou et al. 2019), and even fewer studies compare the heterogeneity of digital technologies' impact across manufacturing sectors (Liu et al. 2021; Zhou et al. 2019). Moreover, there is little recognition of

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[13] According to the ISIC classification, the "industry sector" includes the sectors of manufacturing, construction, mining and quarrying, electricity, gas, and water supply. However, in this study we use the term "industry" synonymous with "manufacturing" (ILOSTAT 2023).

[14] Energy intensity is defined as energy consumption per unit of value added.

the concept of I4.0 in previous studies, and subsequently little diversity of manufacturing-specific proxies for measuring I4.0, as opposed to more widely used indicators of digitalisation such as ICT capital, broadband coverage and mobile internet subscriptions (for a list of indicators, see ITU (undated)). In some studies in the context of China, authors oversimplify the concept of I4.0, for instance, by equating robot use with artificial intelligence (AI) use (Liu et al. 2021, 2022b; Zhang, Liu and Zhu 2022), leaving out the innovation and knowledge dimension of technologies. Additionally, previous studies on robot use in China, mainly frame econometric models around the efficiency and energy-intensity related effects of digitalisation, thereby neglecting the aggregate energy consumption. All in all, it remains unclear whether the proliferation of I4.0 is associated with higher or lower energy consumption and energy intensity in manufacturing.

This study aims to provide an empirical perspective on the relationship between I4.0, energy intensity and energy consumption in Chinese manufacturing sectors over time and investigate the expectation that I4.0 is associated with decreasing energy intensity and energy consumption in industry. Specifically, we ask the following research question: How far is the degree of I4.0 linked to energy consumption and intensity in industry sectors? We address this question by conducting a panel data analysis of the degree of I4.0 and energy consumption and energy intensity in 10 industry sectors over a 14-year period (2006-2019). To this end, we construct a combined index of robot and I4.0 patent intensity as a proxy for the degree of I4.0 in manufacturing sectors.

Our study aims to extend the existing literature in several dimensions. First, we extend the time frame and the granularity of previous studies by differentiating between ten manufacturing sectors in China between 2006 and 2019. Second, to face the lack of indicators and data for I4.0 we introduce a novel way of conceptualising I4.0 and operationalising its measurement by approximating I4.0 through robot intensity and patent intensity. Robot intensity is one indicator reflecting the tangible dimension of the concept of I4.0, i.e., it should be a proxy for the dimension of hardware equipment and automation of manufacturing. Patent intensity is one indicator reflecting the intangible dimension of I4.0, i.e., it should be a proxy for the dimension of knowledge, intellectual property and innovation regarding I4.0. Both indicators have been used before separately in similar studies, e.g., robot data to analyse AI, I4.0 and automation (Liu et al. 2020, 2021; Ramos, Garza-Rodríguez and Gibaja-Romero 2022) and patent data in the context of energy intensity (Ajayi and Reiner 2020) and digitalisation (Li, Li and Wen 2021; Zhang, Gao and Zhou 2023). To the best of our knowledge, however, we are the first to use patent data attributed to sectors in eight I4.0 technology fields as a proxy for I4.0 and to combine robot and patent data to assess their joint impact of I4.0 on energy indicators. Third, we include both energy consumption and energy intensity in the econometric model to investigate differences in the effect of digitalisation on energy consumption and energy intensity and discuss the interaction between energy consumption, energy intensity and I4.0 on the level of sectors in manufacturing in China. This allows us to reflect on the role of I4.0 for absolute reduction of energy consumption as opposed to intensity/efficiency-focused accounts in previous studies.

Understanding the nexus between energy and I4.0 in China could have significance not only for Chinese industry representatives and policy makers. The European Union and countries in other world regions are facing similar challenges in shaping I4.0 to promote the goals of sustainable development. For instance, the EU pursues a “green and digital transition” in industry

(European Commission 2021), aiming to achieve both environmental and digital innovation targets. Moreover, some industrial policy strategies in Asia and Africa draw links between environmental sustainability and digitalisation in industry. However, it often remains unclear in these policy visions how digitalisation will translate into environmental benefits in the economy (Kunkel and Matthess 2020). Thus, empirical evidence of the environmental effects of digitalisation in industry, such as the relationship between I4.0 and energy usage in manufacturing sectors, could inform countries' policy measures to steer the implementation and environmental effects of I4.0 towards the goals of sustainable development.

4.2 Theory & evidence: Impacts of digitalisation and industry 4.0 on energy consumption and energy intensity

Taking into account the broader literature on the effects of information and communication technology (ICT) on the environment of the past 25 years, digital technologies have been theorised to cause direct effects and indirect (including systemic) effects on the environment. Direct effects result from the resources and energy required in production, use and disposal/reuse of digital technologies (Bieser and Hilty 2018). Indirect effects arise, when digital technologies are used in other domains, such as agriculture or industry, and affect environmental indicators in these domains. Systemic effects occur when digitalisation induces long term structural shifts in how and what is produced in the economy (Erdmann et al. 2004; Hilty et al. 2006), which has an effect on energy usage and other environmental indicators in the economy. Furthermore, when viewed from an economic standpoint, the indirect effects of digitalisation in industry on the environment can be decomposed into a scale effect, a technique effect, and a structure effect (Han et al. 2016; Tsurumi and Managi 2010). For the case of energy, these effects can be defined as follows:

- **Scale effect** is the effect on energy consumption that occurs through digital technology's impact on growing the economy (e.g., sales of products and services) (also called income effect, or final demand effect).
- **Technology effect** is the effect of digital technology on energy intensity in other sectors (also called technique effect). It is argued that innovation and technological progress have a reducing effect on energy intensity, since they promote the development of more efficient technology (as a result of the innovation itself) and technological spillover into other areas, and thus lead to more energy efficient production (Huang and Chen 2020; Li et al. 2022).
- **Structure effect** is the effect of digital technology on the size, composition, and value added of sectors which can influence energy consumption and intensity in the economy. For instance, the introduction of digital technologies in the automotive sector may shift the value added from manufacturing to the service sector, as value added grows stronger in the accompanying services (e.g., repair of board electronics) than in the manufacturing of the car (Matthess and Kunkel 2020). This may affect energy consumption and intensity of the sector.

Empirical studies on the environmental impacts of digitalisation come to varying, or even opposite, results (Wang and Xu 2021; Zhang and Wei 2022). Regarding energy consumption, for instance, Schulte, Welsch and Rexhäuser (2016) conducting a multi-country OECD panel investigation find an overall negative relationship between ICT and energy consumption. The direct effect of using ICT and its indirect growth-accelerating effect (scale effect) increase energy demand, whereas the energy efficiency effect (technology effect) and the structure effect reduce energy demand. Han et al. (2016) analysing the impact of ICT on energy consumption in China find that the net effect of ICT is initially negative (until 2014) and then becomes positive. The authors assume that the reason for this U-shaped effect is the industrial structure optimisation through ICT. The optimisation process of moving away from energy intensive industries happened before 2014. The scale effect, including household income growth through ICT, direct energy consumption of ICT as well as lower energy costs outweigh the savings of ICT after 2014 (Han et al. 2016). Applying a machine learning approach to firm level data of 25000 firms in Germany, Axenbeck, Berner and Kneib (2022) find that ICT more frequently leads to an increase than a decrease in energy consumption in the observed firms.

Regarding energy intensity, Zhou, Zhou and Wang (2018) scrutinise the impact of ICT on Chinese energy intensity changes from 2002 to 2012 using a three-tier structural decomposition analysis. Their results indicate that ICT contributed to a 4.54 % increase in energy intensity. However, ICT input in other sectors had an energy intensity decreasing effect. Effects seemed to be stronger in the service sectors and the more technology-intensive sectors. For heavy manufacturing sectors and other energy intensive sectors, the effects were negligible. Wang, Lee and Li (2022), on the other hand, find an energy intensity reducing effect of the use of industrial robots across 38 countries. They argue that increased productivity, optimised factor structures, and technological innovation in production improve energy efficiency, depending on the application field and country. They also find that after the introduction of the concept of I4.0 in 2011 the negative impact of robots on energy intensity increased compared to before 2011, and thus conclude that I4.0 has an energy intensity decreasing effect. Lee, Qin and Li (2022) similarly find a positive relationship between industrial robots the introduction of I4.0 and green technology innovation. Liu et al. (2021) equate industrial robot use with AI use and find that AI use contributed to decreasing energy intensity in Chinese industry sectors by both increasing output value, and reducing energy consumption. They also demonstrate that efficiency gains due to AI vary across industries. The negative effect of AI on energy intensity is found to be most pronounced in technology-intensive sectors, and its positive effect on output value (scale effect) greater in labour- and technology-intensive sectors than in capital intensive sectors. As in the case of energy consumption, several studies come to the conclusion, that there is a non-linear effect of digital technologies on the environment (Axenbeck, Berner and Kneib 2022; Faisal, Tursoy and Pervaiz 2020; Hao et al. 2022; Liu et al. 2021; Wang and Xu 2021). First, digital technologies are found to be associated with increasing energy intensities and then with decreasing energy intensities as the reference variable (e.g., financial development, and technological development) increases.

To conclude, several studies find an energy intensity reducing (technology) effect of digitalisation, using different indicators, such as ICT investment or industrial robot use. Some studies hint to growth inducing effects and the non-linearity of digitalisation's impact on energy, depending on households' and countries' income level. Wang and Xu (2021) reviewing 46 articles on the econometric analysis of environmental impacts of ICT conclude that the variation in results is due to differences in the underlying contexts, study periods, indicators and/or estimators. Zhang and Wei (2022) alert to the omission of system level effects which have led to confounded results in previous studies.

4.3 Methods

4.3.1 Data

Drawing from standard econometric textbooks and a recent review of econometric approaches to the environmental effects of ICT (Croissant and Millo 2018; Henningsen and Henningsen 2019; Wang and Xu 2021), in this analysis we choose an econometric panel data estimation approach and first construct a panel data set with a cross-sectional dimension (N= 10 sectors) and a time dimension (T = 14 years). The dataset is balanced, as each panel member (sector) is observed every year, which results in 140 observations. An overview of the variables in the dataset can be found in Table 16.

Variable (availability)	**Definition**	**Unit**	**Data sources**
Industry 4.0			
Degree of industry 4.0	(Stock of industrial robots divided by real GVA (RVA) (standardized))+ (Stock of industry 4.0 related patents divided by total stock of all patents (standardized))	Standardized index, mean = 0, normally distributed	International Federation of Robotics Industrial Robots Report, China National Intellectual Property Administration (CNIPA) via European Patent Office's PATSTAT database
Industrial robot stock (2006-2020)	Stock of industrial robots, implicit depreciation rate included (depreciation of robots every 12 years)	Number of robots	International Federation of Robotics Industrial Robots Report
Industry 4.0 patent stock (2006-2019)	Stock of industry 4.0 related patents (each including 10% depreciation rate per year)	Number of patents	China National Intellectual Property Administration (CNIPA) via PATSTAT database
Environmental impact			
Energy use	Total final energy consumption in terajoule (TJ) in the end-use industrial sectors	TJ	International Energy Agency (IEA) World Energy Balances 2021 Edition. "Total final consumption"
Energy intensity (2006-2019)	Total final energy consumption in TJ in the end-use industrial sectors per unit of GVA	TJ/US-Dollars	International Energy Agency (IEA) World Energy Balances 2021 Edition. "Total final consumption"
Control			
Gross Value Added (GVA) (2006-2018)* Real value Added (RVA)	Sectoral Gross Domestic Product (GDP); GVA is GDP subdivided by sectors with taxes deducted and subsidies added RVA is GVA adjusted by annual sectoral purchaser price indices	US-Dollars, Millions	OECD Input-Output Table (2021 ed.)
Energy Price Index (2000-2020)	Purchasing price indices for industrial producers of fuel and power	Index (2000 = 100)	China National Bureau of Statistics
Emission intensity of imports (2006-2018)**	Total CO2 emissions embodied in gross imports	1000 tonnes	OECD
R&D Expenditure (2008-2019)***	R&D Expenditure (2008-2019)* R&D Expenditure of large and medium-sized enterprises (2003-2010)	Yuan, Millions	OECD ANBERD, NBS
Trade intensity	Sum of imports and exports divided by GVA	Trade / GVA	OECD Input-Output Table (2021 ed.)
Foreign capital (2006-2019)	Foreign Capital of Industrial Enterprises above Designated Size	Yuan, Millions	NBS

Table 16: Data. Notes: *2019 value extrapolated; assumption: Based on CNBS Value-added of industry, VA has increased in all sectors uniformly as total VA has increased for industry as a whole; ** 2019 is imputed by taking the average growth rate over the past 5 years and multiplying the 2018 value with that rate; *** 2006-2007 missing in OECD ANBERD: Approximation of 2006 and 2007 values by calculating trends (annual percentage changes) in NBS database and applying to last available value in OECD database (e.g. 2008 to 2007 change from NBS used to impute 2007 OECD value); Industry 9 (transport) in the period of 2008-2011 missing: approximation of Industry 9 in the period of 2008-2011 using trends (annual percentage changes) from NBS R&D expenditure of large and medium-sized enterprises.

The degree of industry 4.0 is constructed by standardising and adding industry 4.0 patents and robot intensity for each industry and each year:

Degree of Industry 4.0 = Industry 4.0 patents intensity (standardized) + robot intensity (standardized)

Industry 4.0 patents intensity is constructed by dividing the stock of industry 4.0 related patents (each including 10 % depreciation rate per year) by the stock of all patents in the sector. Our dataset on industry 4.0 related patents is sourced from the China National Intellectual Property Administration (CNIPA) via European Patent Office's PATSTAT database. It has been constructed by aggregating patent applications in eight technology fields: big data and analytics, robotics and autonomous systems, cloud computing, the internet of things, artificial intelligence (AI), 3D printing, digital security, and digital measuring tools and sensors. The technology fields were adapted from Martinelli, Mina and Moggi (2021), and the definitions and IPC codes were adapted from the UK IP Office (UK Intellectual Property Office 2013, 2014a,b,c), Ardito, D'Adda and Messeni Petruzzelli (2018), Martinelli, Mina and Moggi (2021) and the OECD (Baruffaldi et al. 2020).

Robot intensity is constructed by dividing the stock of industrial robots (including full depreciation of robots every 12 years) by the real value added (RVA) generated in the industry sector. The robot data is sourced from the International Federation of Robotics. We standardize both variables (mean = 0, normally distributed).

Energy consumption and energy intensity are used as proxies for the environmental impact of industry sectors. Energy data is taken from the International Energy Agency (IEA). Energy intensity is constructed by dividing energy consumption by RVA. More details on the data preparation and methodology can be found in Appendix A and B.

4.3.2 Estimation strategy

We estimate econometric models of the association between the degree of industry 4.0 and energy consumption as well as energy intensity, respectively, in ten Chinese manufacturing sectors. We specify static, parametric panel models as frequently used in related studies (Wang and Xu 2021) with the following specification:

$$\begin{aligned}\ln(ener)_{it} = {} & \beta_1 I4.0degree_{it} + \beta_2 \ln RVA_{it} + \beta_3 \ln foreign_{it} + \beta_4 \ln RD_{it} \\ & + \beta_5 \ln tradeint_{it} + \beta_6 \ln CO2imp_{it} + \beta_7 PPIener_t + u_{it}\end{aligned} \tag{1}$$

$$\begin{aligned}\ln(enerint)_{it} = {} & \beta_1 I4.0degree_{it} + \beta_2 \ln foreignint_{it} + \beta_3 \ln RDint_{it} \\ & + \beta_4 \ln tradeint_{it} + \beta_5 \ln CO2impint_{it} + \beta_6 PPIener_t + u_{it}\end{aligned} \tag{2}$$

where $ener/enerint_{it}$ is energy use / energy intensity of sector i at time t, respectively; where β_1, $\ldots$, β_7 are estimation parameters; where $I4.0degree$ is the degree of $I4.0$ at time t in sector i;

where GVA, $foreign/foreignint$, $RD/RDint$, $trade/tradeint$, $CO2imp/CO2impint$ are control variables at time t in sector i in levels and intensities, respectively; where $PPIener$ is a control variable for energy prices (measured by the purchasing price index of energy) at time t irrespective of the sector (equal for all sectors); where depending on the estimator used

$$u_{it} = \gamma_i + \delta_t + \varepsilon_{it} \tag{3}$$

with γ_i being a sector specific error, δ_{it} being a time specific error and ϵ_{it} being a random error.

We test various estimators: Ordinary Least Square, one-way fixed effects, two-way fixed effects, random effects and first difference estimators. Comparing the results of various specification allows us to determine how sensitive our results are to changes in the estimators. We use the data analysis software "R". We log-transform (natural logarithm) all variables except the degree of I4.0 (standardized) and PPI (index variable). For each estimator, we test the relevant model assumptions according to standard procedures for panel data analysis (Croissant and Millo 2018; Henningsen and Henningsen 2019). We test for linearity, multicollinearity, error structure (including serial correlation, cross-sectional dependence, heteroscedasticity, and unit roots (i.e. stationarity of variables)). We use the Breusch-Godfrey test (Breusch 1978) which indicates serial correlation in the error terms. We use the Pesaran cross-sectional dependence test (Pesaran 2021), which indicates cross-sectional dependence between the errors of the units of observation (sectors) for the intensities' model but not for the level model. Given the existence of cross-sectional dependence, second-generation unit root tests are necessary. The cross-sectionally augmented Dickey-Fuller test (Pesaran 2007) indicates no unit roots, although our time series might be too short to detect unit roots, as the question of co-integration/unit roots is rather relevant for long time series (Pedroni 2019). Due to serial correlation and cross-sectional dependence, we use cluster-robust standard errors from the "msummary" function in R (option "HC3" recommended for small samples). More details about our methodological approach can be found in the Appendix B.

It should be noted that our estimation strategy does not allow drawing conclusions about causal effects. Specifically, our study design and available data do not allow ruling out endogeneity. For instance, energy intensity of sectors might affect innovation activities in these sectors, thus reverse causality might apply. Additionally, energy consumption is likely to be influenced by other factors not accounted for in the model, such as sectoral policy decisions, which inflicts the problem of omitted variable bias. Therefore, we interpret our results as correlations, informed by our underlying conceptual framework through which we hypothesise and discuss potential causal relationships. Figure 13 summarises our conceptual framework.

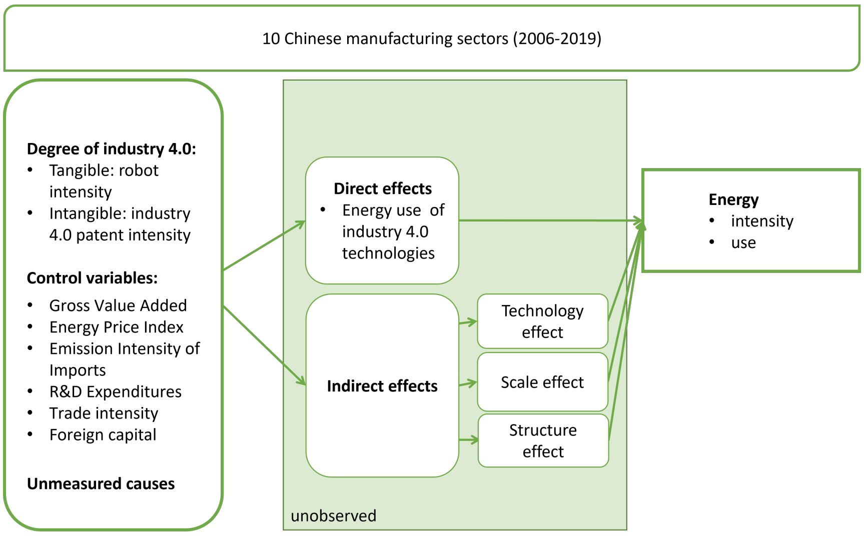

Figure 13: Conceptual framework: The total effect of industry 4.0 on a sector's energy intensity and consumption depends on the size of the direct effect, the technology effect (efficiency changes in sector due to industry 4.0), the scale effect (growth of sector due to industry 4.0) and the structure effect (shift of composition of sector) (Lange et al., 2020), also see section 2. Please note that we do not intend to estimate (decompose) the size of the direct and different indirect effects on energy consumption and intensity. For decomposition studies, please see Zhou, Zhou and Wang (2018).

4.4 Results

4.4.1 Descriptive analysis

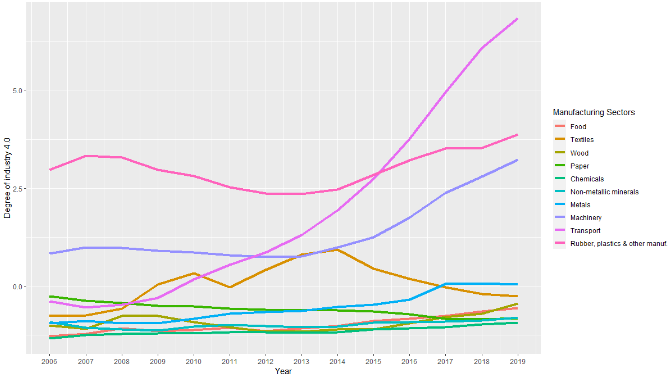

Figure 14: Degree of Industry 4.0, 2006-2019 per sector; Note: due to standardization, values can be below 0

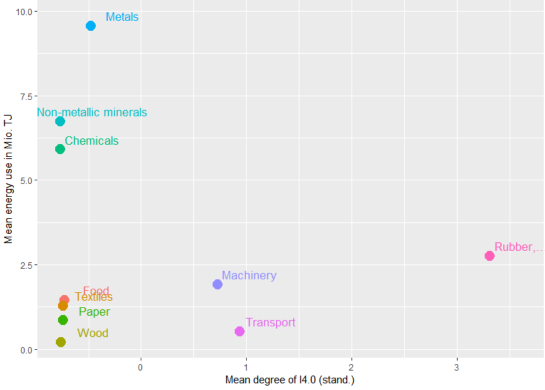

Figure 15: Scatterplot of sectors by mean energy use and mean degree of industry 4.0

The degree of I4.0 (Figure 14) has remained relatively stable for most sectors until 2012, except for the Transport sector, where a steady increase can be observed since 2007. Machinery, Rubber, plastics, and other manufacturing experience an accelerated increase in the degree of I4.0 since 2012. All other sectors remain below average (standardized scale) for most of the observed period.

Energy consumption has increased over time, while energy intensity has decreased over time for all sectors, but remains highest throughout most years for the sectors metals, non-metals, chemicals and rubber, plastics and other manufacturing (see Figures 11 and 12 in section 4.1).

Intensity decrease rates are highest for the sectors with the highest energy intensity to start with.

To better understand sectoral heterogeneity, we plot mean energy consumption and mean energy intensity against mean I4.0 degree (Figure 15). The visual inspection suggests that there are three groups of industries: low energy consumption and low degree of I4.0 in the lower left corner, high degree of I4.0 and low energy consumption in the lower right corner and low degree of I4.0 and high energy consumption in the upper left corner.

To conclude, industry sectors show high heterogeneity in the indicators of interest. Particularly, there are only a few sectors with high degree of I4.0 (machinery, rubber, plastics and other manufacturing), and sectors of high energy intensity and consumption (metals, chemicals, non-metals, rubber, plastics and other manufacturing). This heterogeneity poses challenges to our estimation approach, which we will discuss in the limitations section. In the following, we will explore whether any systematic statistical relationship between these indicators can be detected.

4.4.2 Inference

We report two models with six different specifications each. Model 1 uses energy consumption as the dependent variable, model 2 uses energy intensity as the dependent variable.

Energy consumption	No control variables	Pooled OLS	Time and sector fixed effects	Sector fixed effects	Random effects	First difference
(Intercept)	14.563***	6.409+			11.156***	-0.011
	(0.102)	(3.660)			(1.152)	(0.018)
I4.0 degree	**-0.049**	**-0.152**	**0.032**	**0.019**	**0.019**	**0.011**
	(0.048)	**(0.142)**	**(0.026)**	**(0.018)**	**(0.018)**	**(0.028)**
log(RVA)		0.418	**0.320+**	**0.263***	**0.259***	0.154
		(0.364)	(0.178)	(0.102)	(0.102)	(0.143)
log(realRD2)		-0.419	-0.112	-0.092	-0.091	0.046
		(0.268)	(0.083)	(0.062)	(0.063)	(0.040)
log(trade_int)		0.189	0.027	0.023	0.023	0.009*
		(0.118)	(0.020)	(0.017)	(0.018)	(0.004)
log(PPIener)		-0.112		0.297**	0.292**	0.192*
		(0.474)		(0.088)	(0.091)	(0.074)
log(realforeign)		-0.020	0.071	0.147	0.153	0.130*
		(0.298)	(0.138)	(0.104)	(0.103)	(0.050)
log(CO2imp)		0.818**	-0.081	-0.068	-0.062	-0.034
		(0.291)	(0.055)	(0.057)	(0.055)	(0.025)
Num.Obs.	140	140	140	140	140	130
R2	0.005	0.501	0.427	0.614	0.601	0.151
R2 Adj.	-0.003	0.475	0.282	0.564	0.580	0.102
AIC	4521.3	1109.6	463.4	486.0	495.4	465.1
BIC	4530.1	1136.0	484.0	509.5	521.9	490.9
Log.Lik.	-219.694					
F	1.009					
RMSE	1.16	0.82	0.08	0.09	0.09	0.08

Notes: + $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$, standard deviations in parentheses.

Table 17: Model 1. Dependent variable: Log(energy), independent variables: levels

Energy intensity	No control variables	Pooled OLS	Time and sector fixed effects	Sector fixed effects	Random effects	First difference
(Intercept)	2.763***	4.314***			3.515***	-0.073***
	(0.095)	(0.881)			(0.357)	(0.017)
I4.0 degree	**-0.196****	**-0.177**	**0.033**	**-0.021**	**-0.022**	**0.040**
	(0.061)	**(0.170)**	**(0.030)**	**(0.020)**	**(0.020)**	**(0.049)**
log(RD_int)		-0.497	-0.022	-0.141	-0.146	0.158***
		(0.420)	(0.044)	(0.129)	(0.130)	(0.017)
log(trade_int)		0.184	0.018	-0.011	-0.010	0.006
		(0.135)	(0.020)	(0.022)	(0.022)	(0.005)
PPIener		-0.158		-0.207***	-0.209***	-0.050
		(0.114)		(0.057)	(0.055)	(0.045)
log(foreign_int)		0.011	0.245	0.768***	0.758***	0.295*
		(0.316)	(0.152)	(0.102)	(0.100)	(0.118)
log(CO2imp_int)		0.882*	0.135+	0.213+	0.218+	0.042
		(0.358)	(0.073)	(0.110)	(0.111)	(0.031)
Num.Obs.	140	140	140	140	140	130
R2	0.076	0.453	0.334	0.868	0.861	0.281
R2 Adj.	0.069	0.429	0.173	0.852	0.855	0.246
AIC	1201.6	624.3	2.2	106.5	117.3	-6.2
BIC	1210.5	647.8	19.8	127.1	140.8	16.7
Log.Lik.	-214.233					
F	10.134					
RMSE	1.12	0.86	0.09	0.14	0.14	0.08

Notes: + p <0.1, * p <0.05, ** p <0.01, *** p <0.001, standard deviations in parentheses.

Table 18: Model 2. Dependent variable: Log(energy intensity), independent variables: intensities

Regarding energy consumption as the dependent variable (Table 17), no significant effects of the degree of I4.0 can be detected in either model specification. Real value added and energy price index have a significant positive association with energy in the Random Effects and Fixed Effects specification. Regarding energy intensity as the dependent variable (Table 18) no significant effects of the degree of I4.0 can be detected in either model specification. The energy price has a significant energy intensity reducing effect in the Fixed Effects and Random Effects specification. Foreign capital intensity has a significant positive effect on energy intensity. Figures 16 and 17 summarize the results of the sector fixed effects estimators of Model 1 and 2.

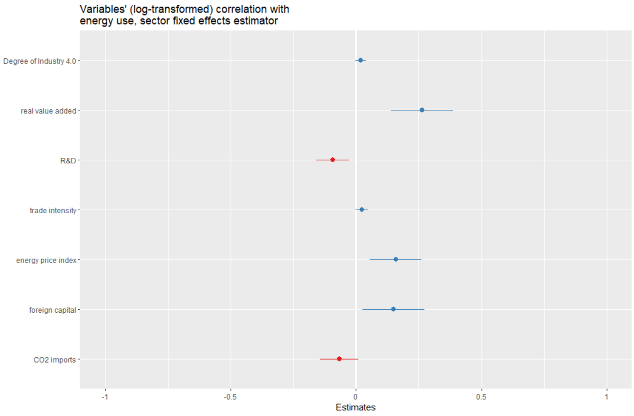

Figure 16: Variables' correlation with energy consumption, sector fixed effects estimator.

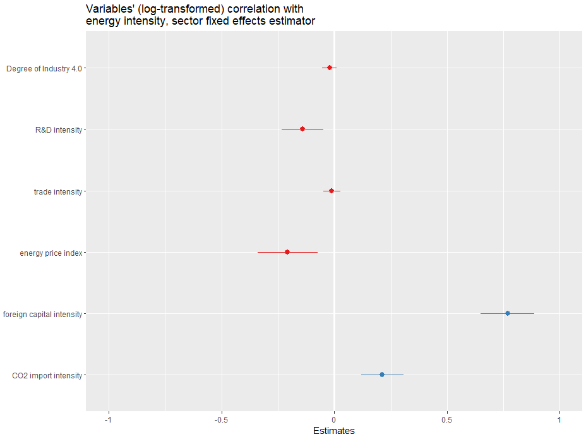

Figure 17: Variables' correlation with energy intensity, sector fixed effects estimator.

4.4.3 Heterogeneity Analysis

We perform one-way fixed effects analyses for energy and energy intensity on subsets of the data, splitting the dataset according to 1) sectors and 2) time. First, we separate sectors according to whether they are comparatively a) high or low energy, as well as b) highly or less digitalised. We calculate the average of energy intensity per sector over time and take those sectors as high energy which are above average. We calculate the average of the degree of I4.0 per sector over time and take those sectors as highly digitalized sectors which are above average. The results are largely in line with the visual inspection of the plots in section 4.1 and with a classification by Calvino et al. (2018) for the OECD context. This results in the following classification:

- "high energy sectors": metals; non-metallic minerals; chemicals; rubber plastics and other manufacturing
- "low energy sectors": food; textiles; wood; paper; transport, machinery
- "highly digitalised sectors": machinery; transport; rubber, plastics and other manufacturing
- "less digitalised sectors": food; textiles; wood; paper; metals; chemicals; non-metal minerals

Second, we separate the data into two time periods (2006-2011; 2012-2019) and investigate if there are differences in the significance of results for each period. The date is chosen because the concept of I4.0 has been published in 2011 and has gained relevance thereafter. However, since the regression on the split time span does not yield any additional significant results, we only report the results of separating sectors according to energy and degree of I4.0.

	High energy sectors	**Low energy sectors**	**High digi sectors**	**Less digi sectors**
I4.0 degree	0.046	**0.040***	0.018+	-0.023
	(0.105)	(0.015)	(0.009)	(0.082)
log (RVA)	0.163	0.214	-0.172	0.357***
	(0.118)	(0.141)	(0.175)	(0.080)
log (realRD2)	-0.037	-0.133*	0.089	-0.169*
	(0.060)	(0.058)	(0.077)	(0.070)
log (trade_int)	0.020	0.017	-0.019**	0.022
	(0.017)	(0.016)	(0.006)	(0.020)
log (PPIener)	0.361**	0.322**	0.561***	0.163*
	(0.103)	(0.113)	(0.130)	(0.073)
log (realforeign)	0.383**	0.090	0.311	0.127
	(0.139)	(0.101)	(0.242)	(0.096)
log (CO2imp)	-0.001	-0.051	0.130*	-0.022
	(0.043)	(0.127)	(0.062)	(0.076)
Num.Obs.	56	84	42	98
R2	0.762	0.625	0.776	0.577
R2 Adj.	0.709	0.562	0.713	0.512
AIC	199.8	268.9	142.0	344.3
BIC	216.0	288.4	155.9	364.9
RMSE	0.08	0.08	0.08	0.09
Std.Errors	HC3	HC3	HC3	HC3

Table 19: Model 3. Dependent variable: Log(energy), independent variables: levels, Sector fixed effects estimator, Notes: + p <0.1, * p <0.05, ** p <0.01, *** p <0.001, standard deviations in parentheses.

	High energy sectors	**Low energy sectors**	**High digi sectors**	**Less digi sectors**
I4.0 degree	0.107	0.002	**-0.019***	-0.076
	(0.099)	(0.021)	(0.007)	(0.112)
log (RD_int)	-0.055	-0.313**	0.217***	-0.343*
	(0.078)	(0.111)	(0.009)	(0.133)
log (trade_int)	0.029	-0.023	-0.056**	-0.021
	(0.044)	(0.034)	(0.016)	(0.028)
PPIener	-0.101+	-0.204*	0.023	-0.201**
	(0.060)	(0.089)	(0.035)	(0.074)
log (foreign_int)	0.887***	0.761***	0.965**	0.662***
	(0.096)	(0.091)	(0.280)	(0.059)
log (CO2imp_int)	0.076	0.484***	0.401	0.339**
	(0.102)	(0.121)	(0.281)	(0.123)
Num.Obs.	56	84	42	98
R2	0.927	0.877	0.896	0.896
R2 Adj.	0.912	0.858	0.870	0.881
AIC	71.8	10.1	-5.7	92.3
BIC	85.9	27.1	6.5	110.4
RMSE	0.10	0.13	0.11	0.13
Std.Errors	HC3	HC3	HC3	HC3

Table 20: Model 4. Dependent variable: Log(energy intensity), independent variables: intensities, Sector fixed effects estimator Notes: + p <0.1, * p <0.05, ** p <0.01, *** p <0.001, standard deviations in parentheses.

Regarding energy consumption, the heterogeneity analysis with regressions on subgroups of the data (highly energy-intensive, low energy sectors; highly digitalised sectors and less digitalised sectors) suggests that the degree of I4.0 has a significant positive association with energy in low energy sectors and a significant positive effect to the 10 % level in highly digitalised sectors (Table 19). Furthermore, in highly digitalised sectors, among the control variables, CO2 embodied in imports is positively correlated with energy consumption. Regarding energy intensity, the degree of I4.0 has a significant negative effect on energy intensity in highly digitalised sectors (Table 20). Among the control variables, foreign capital intensity has a strong positive association with energy intensity. Here, CO2 intensity embodied in imports has a positive association with energy intensity in low energy sectors and less digitalised sectors.

4.5 Discussion

4.5.1 Relationship between the degree of industry 4.0, manufacturing energy intensity and energy consumption

The main intention of this study is to understand how far the degree of I4.0 in sectors is linked to overall energy consumption and energy intensity of manufacturing sectors in China.

Regarding overall energy consumption in manufacturing sectors in China, our results indicate that there is no significant relationship between the degree of I4.0 and energy consumption. In our heterogeneity analysis, the degree of I4.0 has a significant positive relationship with energy consumption in the group of low energy industries. This is in line with the general notion that the digital technologies associated with I4.0, require energy in their operation (direct effect; see Paryanto et al. (2015) and Wang, Lee and Li (2022)). For instance, using robots instead of manual labour in currently less digitalised textiles manufacturing, may likely increase energy consumption of textile manufacturing. Additionally, digitalisation has an economic growth inducing effect (scale effect), which is also indicated by the significant positive association with RVA in our estimations. Economic growth typically increases energy consumption (Salahuddin, Alam and Ozturk 2016; Vu 2011; Wang, Lee and Li 2022; Zhao, Liu and Dai 2021).

Regarding energy intensity, our results indicate that there is no overall significant relationship between the degree of I4.0 and energy intensity. Our results coincide with the results of Zhou, Zhou and Wang (2018) for high energy sectors, who equally find negligible effects of ICT on energy intensity. For the metallurgy industry in China, Lin and Xu (2019) find that the replacement of labour with energy through mechanization of production processes, hinders energy intensity reduction in the sector – an effect which might similarly occur for industry 4.0-induced automation and technological upgrading in sectors. However, there are also several studies which contradict our results, finding an energy intensity reducing impact of robots and industrial digitalisation (Liu et al. 2021; Wang, Lee and Li 2022; Wen, Lee and Song 2021; Zhang, Liu and Zhu 2022). In our heterogeneity analysis, we find such a negative association between I4.0 and energy intensity for highly digitalised sectors, which could be explained by efficiency-inducing effects of I4.0 in already technology-intensive sectors.

We identified several reasons for the differences between our results and previous studies. First, this may have methodological reasons, as explained in more detail in the limitations section. For instance, since patents are a forward-looking indicator, effects on energy indicators may only unfold at a later point in time. Moreover, both robot and patent data, are unequally distributed across sectors. Some sectors thus display very low, some sectors very high degrees of industry 4.0, which has to do with heterogeneous technology uptake in sectors but also with our method of assigning patent data to industry sectors (see limitations section). The resulting low variability of the degree of I4.0 in some sectors over the analysed period makes it more difficult to identify effects of industry 4.0 on energy indicators. Lastly, other study uses different econometric specifications, which also has been found to lead to inconsistent results across studies (Wang and Xu 2021).

Second, the technological change associated with I4.0 and thus presumably its impact on energy is heterogeneous. By including patents in eight technology fields, we captured a wide variety of innovation in the field of I4.0. While it is often argued that innovation can foster energy intensity reductions (e.g., Su, Su and Wang (2021)), it is not clear whether this is true for all I4.0 technologies which we subsume in our patents indicator. For instance, the use of computing-intense algorithms, such as artificial intelligence, requires high amounts of electricity (Salahuddin, Alam and Ozturk 2016) and can be hypothesized to increase energy intensity in sectors that apply such algorithms. Equally, the impacts of hardware and software might be heterogeneous. In a study on the digital economy in China, Wang, Dong and Dong (2022) find that telecommunication services as inputs in other industries have helped to decrease emissions in China, while the increased input of electronic components have contributed to an increase in emissions through indirect structural effects. Ji, Liu and Xu (2023) estimating a two-way fixed effects model of the impact of the digital economy on green development equally do not find a significant effect of the digital manufacturing industry on green development, but find a positive effect of the digital service industry on green development mediated by innovation. Due to a lack of detailed data for industry 4.0 related hard- and software, such heterogeneous effects are difficult to disentangle.

Third, many econometric studies on the effects of digitalisation in industry do not control for the possibility of offshoring (energy-intensive) industrial activities to other countries. While trade is often included as an indicator in related studies, the variable does not allow conclusions about the structure (e.g., energy intensity) of goods and services that are being imported and exported. I4.0 is expected to affect companies' manufacturing location decisions (Butollo 2021), for instance, by reducing transaction costs and facilitating collaboration with international partners. This may lead to changes in domestic and foreign energy intensity of manufacturing, e.g., when energy intensive production steps are outsourced to other countries or more energy intensive inputs are imported from other countries (Hardt et al. 2018). In studies which omit this possibility, energy intensity reductions that arise through digitalisation-related offshoring may mistakenly be attributed to digitalisation itself, and foreign energy intensity increases may be neglected. Regarding China specifically, some of the energy intensity decreases through digitalisation in China detected in previous studies may stem from energy-intensive production steps having been outsourced. To partly capture such effects, we included the indicator CO2 imports as a proxy for energy intensity of imported goods. We find significant positive associations between CO2 imports and the degree of I4.0, suggesting that a higher degree of I4.0 is linked to higher CO2 imports, but further research is required to understand the underlying dynamics.

Last, irrespective of how large the energy intensity reducing effects of industry 4.0 are, it should be noted that energy intensity changes can have different origins and that this may affect the effectiveness and desirability of energy intensity reductions from an environmental point of view. As Hardt et al. (2018) point out, energy intensity changes can be differentiated into 1) a component of thermodynamic conversion efficiency and 2) a component of changing monetary output per unit of useful exergy. If energy intensity (energy consumption divided by real value added) decreases mainly due to increasing real value added (case 2), as found for the case of energy intensity reductions in the UK (Hardt et al. 2018), the technology-driven increase in conversion efficiency (case 1) is much smaller than expected. In other words, energy intensity reducing impacts of I4.0 might stem from a scale (growth inducing) effect rather than from a technology effect. Scale effect driven energy intensity effects have been found for the case of robot adoption in Chinese firms (Huang, He and Lin 2022) and for the digital economy in China (Xue et al. 2022). What does this mean for the relationship between energy, energy intensity and industry 4.0? As argued above, the expectation that I4.0 will not only contribute to energy intensity reductions but also to absolute energy reductions may be dampened. If energy intensity reductions mainly result from scale effects, then efficiency increases may be compensated by the simultaneous scale effect. This digital rebound effect makes it difficult to achieve aggregate reductions of energy consumption. Studies by Brockway et al. (2017) who find a large energy rebound of technological change in China between 1981 and 2010 and Jin and Yu (2022) who detect a rebound effect of ICT in energy-intensive industries in China support this concern.

4.5.2 Other drivers of changes in energy consumption in manufacturing sectors

Chinese energy consumption and energy intensity in manufacturing are affected by a number of other drivers, such as policy interventions (Song and Zheng 2012), R&D (Chen et al. 2019) and renewable energy development (Haldar and Sethi 2022; Liu et al. 2022a). Two drivers which may be particularly relevant in the discussion of the impact of I4.0 on energy indicators are discussed below.

Research and development

Huang and Chen (2020) show that there are differences in the energy intensity reducing effect of R&D at different stages of the innovation process and by different actors. Effects are found to be higher in the experimental and developmental stage than in basic research, and higher if performed by industrial enterprises than by higher education institutions. The authors highlight that higher human capital, defined as the average years of education, has a positive effect on energy intensity reduction, as it increases absorptive abilities for technological innovation of companies. Thus, transferred to I4.0 innovation, similar questions about mediating factors may arise: Who produces I4.0 innovation at which stage of the industrial innovation process, and do human capabilities exist (in the firm) to enable absorption of innovation, in order to reduce energy consumption and intensity?

Renewable energy development

Liu et al. (2022a) find that renewable energy development first has an energy intensity increasing effect, which reverses for high levels of per capita GDP (56,5 thousand yuan). Nonetheless, employment of renewable energies can help to reduce emissions, and the emission-reducing effect of renewable energies has been found to be strengthened by R&D (Cheng et al. 2021). The digital economy seems to play a role in renewable energy development, too. Shahbaz et al. (2022) show that, mediated by governance, digital economy can have a positive role for the employment of renewables. Thus, to the question arises how I4.0 can specifically help to replace fossil fuel-based processes with renewable energy-based processes in manufacturing. For instance, a 10-year study on flexibilisation of energy-intensive industries (e.g., glass manufacturing, raw material melting and electric steel) in the German context investigates the potential of industrial demand-side management and the role of information technology for flexibilisation in the energy market (SynErgie 2022).

4.5.3 Limitations

There are several limitations to our data and methodology that might lead to bias in our results.

First, our concept and measurement of I4.0 can be challenged. While we acknowledge that I4.0 refers to a broad manufacturing transformation, which is coined by interactions between the technological, organisational and human dimensions, we only analyse a fraction of the variables that may indicate such a transformation. For instance, Beier et al. (2020c) provide a list of features of the concept of I4.0, such as employees, collaboration, and decentralization, which we have not captured in our analysis. The reason for this narrow focus is the (un-)availability of time series or panel data on additional features of I4.0 on a sectoral level in China. Additionally, due to the relatively recent emergence, broadness and interdisciplinarity of the concept of I4.0, no unified definition and measurement standards have been determined yet (Beier et al. 2020c; Culot et al. 2020). An extensive review of data has been performed prior to the analysis to identify how other research has dealt with this issue. It has been concluded that few other relevant dataset were available on the sector level in China to perform the desired research. We decided to use a yet less common indicator for the measurement of I4.0, namely I4.0 patents. We believe that patents are a good proxy for innovative endeavours, especially in the field of I4.0 where recent technology developments could not otherwise be captured (Laffi and Lenzi 2021). Patent indicators are also highly correlated with R&D, a widespread indicator of innovation activity. We combine this indicator with robot stock, an indicator which has repeatedly been used to analyse I4.0 and AI in previous works (Li et al. 2022; Liu et al. 2020, 2021; Matthess et al. 2023; Zhang, Liu and Zhu 2022).

Second, notwithstanding the advantages of the data used, it comes with its limitations. Regarding robot data, a large share of robots falls in the category “unspecified” and no further classification is possible. This number could be as high as 45 % (Jurkat, Klump and Schneider 2022) Moreover, the lack of continuous depreciation of the robot stock does not reflect typical capital decumulation processes assumed in the mainstream literature. Another downside is that robots developed in-house are also not counted in the statistics. Lastly, there is no quality measurement incorporated in the International Federation of Robotics measure, thus each industrial robot is counted as one irrespective of its monetary and use value (Jurkat, Klump and Schneider 2022). Regarding patent data, patents are not classified into sectors in patent offices (see further explanation in Appendix B). They are only assigned patent classification codes by patent examiners to identify them (e.g., the “IPC” or the “CPC” classification). We therefore had to convert the patent data to sectors (NACE 2-digits), which we accomplished by matching the patent data at the applicant/firm-level to the ORBIS database. This means that only those patents could be matched, whose company’s information are in the ORBIS database. However, we assume that those companies who have more financial means for research activities are more likely to be represented in the ORBIS database than smaller companies with fewer patenting activities. Additionally, this leads to a concentration of patents in few sectors, where the largest innovator firms are subsumed. By applying logarithmic transformations in the regression analysis, we smooth the distribution. Furthermore, there is reason to believe that many patents have little value (Park and Park 2006). However, since we are only looking at one country and compare sectors, we do not assume that there are systematic differences in the share of patents with little value across industries. Lastly, not all inventions are covered by patents (e.g., open source technologies) and applicants use other appropriation mechanisms to reap benefits from their inventions. For instance, a company might be highly digitalised but does not pursue patenting activity. While these are valid concerns, we again assume that there are no systematic biases with regard to the choice of appropriation mechanisms.

Third, as noted above, our estimation strategy does not allow us to report causal effects. It would have been interesting to understand the counterfactual energy consumption and energy intensity developments, would I4.0 not be present in a sector, or the causal impact of the introduction of I4.0 in a manufacturing sector on energy. We considered possible ways to estimate causal models, for instance, by measuring the link between digital technologies prior to and after a policy intervention, such as a funding scheme for I4.0, through a difference-in-difference approach. However, we could not identify a suitable causal modelling approach for our research question, since we view the proliferation of digital technologies as a gradual process with no clear time marks (such as the introduction of the term I4.0 as done by Lee, Qin and Li (2022) and Wang, Lee and Li (2022)) and also intertwined with other developments whose influences we could not rule out due to limited panel data availability for China (which would entail omitted variable bias).

Finally, another limitation of our study is our narrow sustainability concept. Energy use is only one of many environmental implications of digitalisation in industry, and it also has numerous social implications, such as a changing task profile and polarisation of wages. Again, due to limited data availability, we focus on energy and hope that data sources are continuously being generated to allow future research to take a deeper look into other sustainability aspects.

4.5.4 Future research

Future studies could improve our research in several dimensions. The concept, measurement, and data of I4.0 should be improved. Recent efforts to develop shared definitions and standards of I4.0 in practice will help researchers to refine their frameworks for analysis. More data on other characteristics of I4.0 should also be gathered and assessed. For instance, Chinese data on employees' ICT skills and the employment of ICT specialists could be evaluated to include the human dimension of I4.0, as done on the EU level by Matthess et al. (2023). Moreover, company level data and provincial level data on I4.0's technological, social and organisational features should be collected over time to track developments on a more granular (firm or local) level, including specific technologies' potential and risks in different industrial application fields and geographical regions. Regarding causality, case studies of the firm and sector level over time quantitatively and qualitatively measuring I4.0's effect on energy savings could alleviate some shortcomings of statistical analyses, and the case of Chinese manufacturing could be compared to other world regions' experiences.

More insights are also needed into the international relocation of environmental burden through I4.0. In the context of China, in particular, it would be interesting to explore in more detail how energy-intensive industries can be made more environmentally friendly while avoiding that energy-intensive processes be moved to locations where energy might be cheaper or environmental regulations less strict. Pappas et al. (2018) discuss the risk of industrial relocation of manufacturing for the environment for the examples of India and Indonesia. The emission intensity in these countries, being destinations for Chinese offshoring in the iron and steel sector and the non-metallic minerals sector, respectively, is double the emission intensity in China. Similarly, if firms continue to increase cloud capacities and outsource tasks to digital service providers, energy consumption might shift to other sectors (e.g. telecommunication services sector) in the same country, or other countries, and might not be accounted for in a (manufacturing) sector-specific, national statistic. Thus, in future studies, it will be interesting to take an international perspective on I4.0's impacts, e.g., by including closely related trade partners of China and analyse the joint impact of I4.0 on sectoral energy intensity and consumption.

Regarding the concept of sustainability, research is currently focusing on energy and emissions, but more data should be made available and evaluated by researchers on other environmental and social effects of I4.0 in Chinese manufacturing sectors. For environmental indicators, material input/throughput, utilization and disposal of industrial wastes, land use associated with digital infrastructure, (e-)waste generation and environmentally friendly sourcing of digital technologies (Dong et al. 2018) should be assessed to determine the overall environmental impacts of I4.0. For social indicators, it would be particularly interesting to analyse possible trade-offs between social and environment effects of I4.0, for instance in a scenario where digitalisation would reduce energy consumption but simultaneously reduce employment opportunities of less skilled workers and thus increase social inequalities.

4.6 Concluding remarks

Energy consumption in industry made up 38 % of global final energy consumption (169 EJ) in 2021 with a 5 percentage point growth since 2000 (IEA 2022). China is the largest contributor to this increase (Liu et al. 2022b). Energy demand is projected to continue to grow and increasing renewable energy capacities which made up less than 3 % of Chinese energy production in 2019[15] will arguably not suffice to achieve ambitious decarbonisation targets. With increasing political and industry interest in leveraging industry 4.0 (I4.0) for sustainability in industry, it is crucial to understand how I4.0 impacts energy consumption and other sustainability indicators, but there is currently no scientific consensus on digitalisations' environmental effects. In this study we analysed the link between I4.0, energy consumption and energy intensity in ten manufacturing sectors in the period between 2006 and 2019 in China through panel data analysis. We found that there is currently no clear trend that I4.0 has an either positive or negative effect on energy consumption and intensity in manufacturing sectors, in contrast to several recent studies which posit an energy intensity reducing effect of I4.0. We found differences in the correlations between less and more digitalised and less and more energy using sectors, pointing to heterogeneous effects in sectors. We raised and discussed hypotheses about why energy intensity reduction, including through I4.0, may not necessarily lead to reductions in energy demand. On a conceptual level, scale effects and other energy demand increasing structural effects of I4.0 may be larger than its energy intensity reducing structural and technology effects. Specifically, I4.0 may entail digital rebound effects in industry (Jin and Yu 2022; Kunkel and Tyfield 2021) and lead to increasing relocation of energy-intensive industrial activities to other countries. We conclude that a narrow focus on the reduction of energy intensity through I4.0 can be ineffective for decarbonisation if it mainly results in energy-intensity decreasing output increase and possibly to an overall increasing total energy consumption. Other factors should be considered in the design of I4.0 measures, such as its impact on industrial relocation, heterogeneous and sector-specific impact of different digital technologies, human capabilities to adopt innovations and steer them towards sustainability, and the simultaneous integration of renewable energies in manufacturing sectors. Lastly, other sustainability indicators should also be taken into account, such as resource consumption and e-waste through digital technologies.

The novelty of the analysis was a) to use more recent and more granular data for manufacturing sectors than previous studies, b) to approximate I4.0 with patent and robot data as opposed to general digitalisation indicators used in similar studies (such as broadband coverage), c) to discuss the interaction between energy consumption, energy intensity and I4.0 in China and its implications beyond the country case. This allowed us to reflect on the role of I4.0 for absolute reduction of energy consumption as opposed to efficiency-focused accounts, and point to global challenges, rather than isolating the debate to China. However, our approach also entailed a set of limitations, e.g., we analysed a relatively small and skewed dataset, sensitive to changes in the econometric modelling; and we did not construct a causal model, instead analysing correlations between indicators. Nonetheless, we deem our study a valuable contribution to the debate by shedding light on the assumptions, omissions, and limitations of previous statistical analyses of I4.0. Specifically, we highlighted that important variables may be missing in previous studies and that the positive framing of the environmental benefits of I4.0 presented in policy or industry strategies and by scientific research may also contribute to bias in statistical analyses.

We close with some industry and policy recommendations to help make I4.0 contribute to

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[15] The term renewable energies refers to solar thermal, wind, non-specified biofuels/waste, solar PV; own calculations based on IEA (2021b).

more environmentally sustainable manufacturing. In China, special attention needs to be paid 1) to conceive adequate sectoral measures and monitoring to steer I4.0 towards sustainability, particularly in the most energy using sectors, where rebounds are expected to be large (Jin and Yu 2022), 2) to the prevention of offshoring of energy intensive production processes, including due to I4.0, and 3) to the absolute reductions of energy consumption and emissions, even under a value added growth paradigm. First, due to the growth inducing effect of I4.0, the specific mechanisms and effects through which specific technologies affect energy consumption heterogeneously need to be understood to decide which (sectoral) policies might help to reduce the absolute environmental burden of industry and under which framework conditions. Second, political commitment and international agreements should prevent that I4.0 leads to an increased off-shoring of energy-intensive manufacturing processes to countries with lower environmental standards. Third, I4.0 in manufacturing should therefore be directed in its conception towards the absolute reduction of energy demand and curbing emissions along the entire value chain. The Chinese government's current focus on upgrading industrial structure through innovation, in order to induce growth in value added and achieve energy intensity reduction targets set in the Five-Year-Plans should be complemented by ambitions to reduce energy intensity along the entire value chain. For instance, supply chain wide approaches to sustainability through I4.0 need to be fostered (Kunkel et al. 2022), such as through the circular economy initiatives in the EU and China (European Commission 2020a; NPC 2018), and green supply chain measures (Sheng et al. 2022). Moreover, the 2021 China Energy work conference (Liu et al. 2022b) called for the introduction of a "dual control" system covering total energy consumption and energy intensity, which might help to limit rebound effects. Structural change towards a post-growth industry (Hardt et al. 2021) would certainly also be helpful to save energy. If growth targets, however, remain at the center of Chinese policy-making in the short-term, a recent study suggests that a state policy aiming at a 2-degree global warming with deep emission cuts would lead to larger growth rates than the baseline scenario (Kejun et al. 2021). Whether larger growth rates are desirable from the viewpoint of other environmental indicators (resource use, biodiversity, etc.) is another open question – but at least, a transformation of traditional manufacturing towards environmental sustainability goals may be a first step to help steer the environmental outcomes of I4.0.

Data Availability

- Industrial robot stock: Proprietary data from International Federation of Robotics
- Patent stock: Partly proprietary data from European Patent Office's PATSTAT
- Energy data: Proprietary data from International Energy Agency (IEA) World Energy Balances 2021 Edition
- OECD Input-Output Table: Public data from the Organisation of Economic Co-operation and Development (OECD)
- China National Bureau of Statistics (NBS): Public data from China National Bureau of Statistics
- OECD ANBERD: Public data from the Organisation of Economic Co-operation and Development (OECD) STAN Structural Analysis Database

Data sets can partly be made available upon request.

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CRediT authorship contribution statement

Stefanie Kunkel: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Validation, Writing — original draft, Writing — review & editing; **Peter Neuhäusler**: Data curation, Methodology, Validation, Resources, Writing — original draft, Writing — review & editing; **Marcel Matthess**: Conceptualization, Data curation, Methodology; **Melissa Dachrodt**: Conceptualization, Data curation, Methodology.

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Appendix

Appendix A: Data preparation

Industrial robot data

The industrial robot data used in this study stems from the International Federation of Robotics. This is a private company, reporting robot data since 1993. The International Federation of Robotics definition of industrial robots builds on the definition of the ISO 8373:2012 where a robot is defined as an “actuated mechanism programmable in two or more axes with a degree of autonomy, moving within its environment, to perform intended tasks” (§ 2.6). An industrial robot (as opposed to a service robot) is an “automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications” used “in industrial automation applications” (§ 2.9). The industrial robot data is generated by contributions from all major industrial robot suppliers worldwide which report data on robot installations by country, industry, and application to the International Federation of Robotics Statistical Department. Secondary data by national robotics associations is used to complement and validate the data. In the case of China, since 2013, the Chinese Robot Industry Alliance provides data from Chinese robot suppliers. Regarding depreciation of robots, the International Federation of Robotics assume an average use time of 12 years, with immediate withdrawal afterwards (IFR 2021).

Patent data

We use patent data from the EPO Worldwide Patent Statistical Database (PATSTAT), which provides bibliographical patent data from more than 100 million patent documents from leading industrialised and developing countries. Specifically, for the case of China, we use patent data from the China National Intellectual Property Administration (CNIPA). All patents in our sample are counted according to the year of their first application worldwide, commonly called the priority year. This is the date that comes closest to the R&D. Furthermore, we count patents according to the “inventor principle”, i.e. patents are assigned to the country where the inventor is located (e.g. Siemens is a German company, but if Siemens China branch would file the patent, it would count in the Chinese statistic). This is typically where the R&D has been performed. In order to delineate the technology fields in our data, we make use of one of the most common classification schemes for patents, namely the International Patent Classification (IPC), in which patents are classified according to their technical implications. We combine the IPC based searches with keyword-based searches in the title and abstract of the patents for some fields (for some methodological notes, see Montecchi, Russo and Liu (2013)). The technology field definitions and IPC codes were adapted from the UK IP Office (UK Intellectual Property Office 2013, 2014a,b,c), Ardito, D’Adda and Messeni Petruzzelli (2018), Martinelli, Mina and Moggi (2021) and the OECD (Baruffaldi et al. 2020).

In our analysis, we compare industry sectors. However, patents are only classified according to their technological implications but not alongside sectors. We therefore have to convert the patent data to sectors (NACE 2-digits), which is accomplished by matching the patent data at the applicant/firm-level to the ORBIS database by Bureau van Dijk. ORBIS is a company database including information on nearly 400 million companies and entities across the globe. In order to connect the two databases, we performed a matching on the basis of applicant/company names. After a cleaning of the company and person names (e.g. conversion to lowercase letters, removal of special characters and umlauts as well as spaces, removal of legal forms), we computed the similarity scores between the two names based on the Levenshtein distance. The Levenshtein distance is a calculation of how many edits would be needed in order to align two text-strings. The lower the number of edits necessary to align two text strings, the higher the similarity between the two. All values that exceed a pre-calculated threshold (t>0.89) are interpreted as a match. Based on this matching, we can assign patents to NACE codes based on the NACE code of a company. Lastly, we scanned a random sample of 156 patents by hand and identified approx. 13 % of the patents as potentially inappropriate for the respective category, which we deemed an acceptable error quote.

Figure 18 shows a scatterplot of mean I4.0 patent intensity and mean robot intensity over the observed time period in the ten manufacturing sectors. The plot reveals that the majority of sectors have both relatively low patent and robot intensity. Within this group, textiles and paper show the highest mean I4.0 patent intensity, whereas metals shows the highest mean robot intensity. Three sectors stand out, namely machinery rubber, plastics and other manufacturing and transport, which show higher mean values in both indicators than the other sectors.

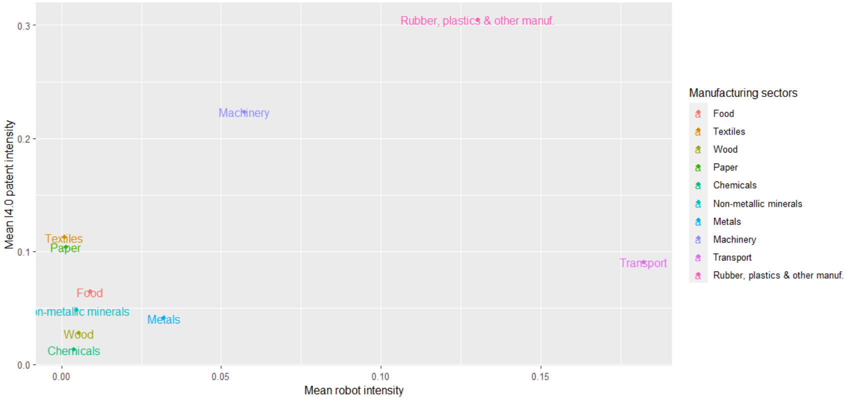

Figure 18: Scatterplot of sectors by mean robot intensity & mean I4.0 patent intensity over time

Energy Data

We use energy data provided by the International Energy Agency (IEA) since 1971 and covering up to 95% of the global energy supply. The IEA provides the World Energy Statistics as well as the World Energy Balances. The IEA data can be accessed with the Beyond 20/20 Browser. It should be noted that that some data is excluded from the IEA database: energy used for transformation processes and for own use of the energy producing industries, backflows from the petrochemical industry, international aviation bunkers and international marine bunkers except for the world total (here they are reported as world aviation bunkers and world marine bunkers in transport)". For further methodological notes on IEA see database documentation (IEA 2021a) and website information (IEA World Energy Balances).

Whereas the World Energy Statistics contain commodity balances – key energy statistics provided in original units for the different types of energy sources, the World Energy Balances are an accounting framework of the combined national commodity balances and provides all the data in a common energy unit. Energy balances help to understand product transformation processes and shine a light on the connections among them to reveal how different energy types are being used. Employing a common energy unit permits users to see the total amount of energy used and the respective contribution of the different sources, for the whole economy and each individual consumption sector. Moreover, it enables the development of various aggregated indicators (e.g. consumption per unit of GDP) and is a frequently used data source for a variety of energy-related research. Hence, our analysis uses the World Energy Balances.

The World Energy Balances contains energy balances for 74 countries and 10 regional aggregates. The energy balances are expressed in tonnes of oil equivalent, defined as 10^7 kilocalories (41.868 gigajoules). For the People's Republic of China, which joined the IEA as an association country in 2015, data are available starting in 1971.

Regarding the calorific value of each fuel, the IEA has opted to base their energy balances on net energy content, which excludes the energy lost to produce water vapour during combustion. Overall, the net calorific values adopted by the IEA are country-specific, time-varying and for some products flow dependent. For most products, they are supplied by national administrations and for oil products, they are based on regional default values. In the matter of another important methodological choice, the IEA has adopted the following principle: "the primary energy form is the first energy form downstream in the production process for which multiple energy uses are practical" (International Energy Agency 2022b, p. 381). This leads to the choice between electricity for primary electricity (hydro, wind, tide/wave/ocean and solar photovoltaic) and heat for heat and secondary electricity (nuclear, geothermal and solar thermal) as a primary energy form. After the primary energy form has been established for all electricity and heat produced from non-combustible sources, the IEA follows the physical energy content method to compute the corresponding primary energy equivalent amounts (International Energy Agency 2022a,b). Regarding the relationship between energy intensity and energy efficiency, aggregate energy intensity can also be viewed as the weighted average of energy efficiency across sectors (i.e. energy efficiency in a sector times the ratio of the sector's contribution to GDP) (Song and Zheng 2012). Thus, we refer to (sectoral) energy efficiency and (sectoral) energy intensity complementarily.

Appendix B: Details on methodology

Mapping sectors

To combine different data sources in our analysis, we map several classifications of manufacturing sectors onto each other, as shown in Table 21. We create 10 joint sectors for our analysis, which are largely compatible with international classification schemes such as NACE (see last column). As energy use is our main dependent variable of interest, IEA sector classifications as described in IEA (2021a) build the basis for our sector mapping. IEA distinguishes between ten manufacturing subsectors. Due to data availability limitations, we combine two subsectors and create a new category "Other", arriving at ten manufacturing subsectors.

No.	Name	IEA	IFR	China NBS*	OECD Stat	NACE
1	Foods	Food and tobacco	Food products and beverages, Tobacco products	Food products, beverages, tobacco products,	Food products, beverages, and tobacco	C10-C12
2	Textiles	Textile and leather	Textiles, leather, wearing apparel	Textiles, wearing apparel, leather and related products	Textiles, textile products, leather and footwear	C13-C15
3	Wood**	Wood and wood products (excl. furniture)*	Wood and wood products (incl. furniture)**	Wood and products of wood and cork, except furniture; articles of straw and plaiting materials	Wood and products of wood and cork	C16
4	Paper	Paper, pulp and printing	Paper and paper products	Paper and paper products, printing and reproduction of recorded media	Paper products and printing	C17-C18
5	Chemicals	Chemical and petrochemical**	Plastic and chemical products, pharmaceuticals, cosmetics, unspecified chemical, petroleum products****	Chemicals and chemical products, medicines and chemical fibres	Chemical and chemical products; Pharmaceuticals, medicinal chemical and botanical products	C20-C21
6	Non-Metal	Non-metallic minerals*	Glass, ceramics, stone, mineral products n.e.c.	Non-metallic mineral products	Other non-mineral products	C23
7	Metal	Iron and steel	Basic Metals, Metals unspecified	Basic metals, non-ferrous metals	Basic metals	C24
8	Machinery	Machinery	Metal products (non-automotive), industrial machinery, electrical/electronics	Fabricated metal products, except machinery and equipment, computer, electronic and optical products, Electrical Machinery & Equipment, machinery, and equipment n.e.c.	Fabricated metal products, Computer, electronic and optical equipment; electrical equipment; machinery and equipment n.e.c.	C25-C28
9	Transport	Transport	Automotive, other vehicles	Motor vehicles, trailers and semi-trailers, other transport equipment	Motor vehicles, trailers and semi-trailers, other transport equipment	C29-C30
10	Other	Industry not elsewhere specified (incl. 22, 31, 32, 33)	All other manufacturing sectors, rubber and plastic products without automotive parts	Other manufacturing, Plastics, rubber and plastics products, Manufacture of furniture Manufacture of Articles for Culture, Education, Arts and Crafts, Sport and Entertainment Activities *	Rubber and plastics, Manufacturing n.e.c.; repair and installation of machinery and equipment	C22, C31, C32, (Misc.)

Table 21: Industry sector mapping, Note: *NBS data is available in varying levels of granularity across sectors and time, several aggregations and decisions had to be made. For instance, manufacture of articles for education might be counted in paper & print in the NACE, while the similar category "manufacture of articles for culture, education, and sports" is sometimes subsumed in "other" in China, **Our sector "Wood" excl. Furniture whereas International Federation of Robotics data includes furniture; ***IEA sector "Chemical and petrochemical" excludes petrochemical feedstocks and thus excludes rubber and plastics, rubber & plastics are incl. in "industry not elsewhere spec.“ **** We exclude C19: Manufacture of coke and refined petroleum products from our analysis as energy data for these products is counted among "Energy Industries". We excluded this category from our all other data sources where possible, in the International Federation of Robotics data, however, category "Unspecified chemical, petroleum products" includes robots used in C19: Manufacture of coke and refined petroleum, thus number of robots is inflated in this category, roughly 25-50 % of robots fall into the category "Unspecified chemical, petroleum products" each year.

Constructing the index "degree of industry 4.0"

To construct the index "degree of industry 4.0", the values of I4.0 patent intensity and robot intensity are combined. Robot intensity, defined as the stock of industrial robots divided by real GVA, and I4.0 patent intensity, defined as the stock of industry 4.0 related patents divided by total stock of all patents are both standardised (mean = 0, normal distribution) for each observation (140) and added. For instance, industry sector "food" in 2006 has a standardised robot intensity of -0.396 and standardised patent intensity of -0.42, resulting in a degree of I4.0 of -0.81. Due to standardisation, values can be below 0.

Table 22 shows the mean of the standardized degree of I4.0 of each sector over time, ordered from lowest to highest degree of I4.0.

Sector	**Mean degree of Industry 4.0 (standardized)**
Chemicals	-1.2
Wood	-1.06
Non-Metal	-0.87
Metal	-0.86
Foods	-0.68
Paper	-0.38
Textiles	-0.30
Transport	1.18
Machinery	1.27
Rubber, plastics and other manufacturing	2.73

Table 22: Mean degree of Industry 4.0, calculated as the standardized sum of I4.0 patent intensity and robot intensity

Accounting for price differences over the time span

To account for changes in price levels over time in China, we use purchasing price indices for industrial producers (PPI) (preceding year = 100) available from the CNBS. We construct PPI for our 10 sector classification system by averaging the PPI levels of multiple sectors, which we had aggregated according to our sector mapping. We create chain linked PPI with the base year 2003 (2003=100) (Wang et al., 2019). As the PPI is only available from 2004 onwards, we use the General Producer Price Index (not differentiated by sectors) for the years 2000-2002. We deflate our monetary variables: Value Added (at basic prices), R&D Expenditure and foreign investment by dividing the nominal annual value by the PPI to obtain deflated values.

Pre-analysis: Data validation & pre-tests

We performed several checks to validate our data. We checked compatibility of our energy data from the IEA with Chinese NBS energy data. We checked correlation between OECD Input-Output data and Chinese Industry Sales value data.We looked at the distribution of the non-transformed variables (QQ-plots), outliers and checked for missing values. While we do not observe many “within wave missings” we are concerned with “whole-wave missings” (Young and Johnson 2015) due to different time availabilities of data sources. We impute several data points as described in Table 2: Data. We checked the collinearity of variables through the variance inflation factor. Furthermore, we created scatter plots of each independent variable against the dependent variable to check for linearity of the relationship between the variables.

5

Summaries of the three studies

The first study investigated expectations of policy makers and observed effects regarding the relationship between digital transformation and environmental sustainability in seven countries of the Global South in Africa and Asia. We conducted a qualitative content analysis of 13 digital and industrial policy documents. Firstly, we established that the majority of the policy documents we had initially scanned (25 of 38), lacked any expectations regarding the effects of ICT on the environmental sustainability of industrial development in low- and middle-income countries. Secondly, for those 13 documents that we examined more closely, we categorised expectations based on whether they referred to direct or indirect environmental effects, as well as whether they were perceived as opportunities or risks for environmental sustainability. Our analysis showed that policies express a broad range of vague expectations focusing more on positive indirect impacts of the use of ICTs, e.g. enhanced energy efficiency and resource management, than on negative direct impacts of ICTs, e.g. electricity consumption of ICTs. Thirdly, we categorised the expectations into four subfields, namely resource efficiency, sustainable energy, transparency and systemic effects, and discussed noteworthy examples from the policies in these four subfields. We proposed that there may be a window of opportunity for digital and industrial policies in the Global South to stimulate a digital and industrial transformation that has environmental sustainability at its core. The study provided empirical insight into differences and similarities in visions for technology held by policy makers in countries in the Global South, and also highlighted gaps between scientific evidence, implementation, and policy makers' expectations. It built a bridge between technology-centred digitalisation and policy research and helped to identify opportunities, risks, and fields of action regarding digitalisation in industry and sustainability that emerged from the political discourses in countries in the Global South.

The second study assessed the extent to which digital technologies are being utilised in supply chain collaboration in a sample of firms and to examine how supply chain representatives perceive the opportunities, risks, and obstacles of digital technologies regarding collaboration on environmental sustainability in electronics supply chains. We conducted 18 expert interviews, ten with international buying firms and eight in written format with Chinese supplier representatives from the electronics sector, and used qualitative content analysis to investigate our research questions. We found that a broad range of digital technologies with varying digital maturity levels, which we classified into low (basic digital technologies), intermediate (electronic data exchange interfaces, ERP systems, among others) and advanced (industry 4.0 technologies), were currently being used in supply chain collaboration. However, their use for sustainability purposes was still limited. We introduced the concept of "digital environmental upgrading" to refer to the integration of digitalisation into the process of "environmental upgrading" which is viewed as a means of increasing environmental sustainability in technologically less advanced countries through participation in global value chains. Digital environmental upgrading was proposed to help create collaboration between supply chain partners, provide training opportunities and generate digital innovation with respect to environmental sustainability, that is shared between firms with different technical capacities along the value chain. We discussed opportunities, risks, and obstacles inherent in the use of digital technologies in supply chain collaboration for sustainability related to technical, political and organisational aspects, such as concerns regarding intellectual property protection in (sustainability) data sharing, and the current lack of political and economic incentives to promote sustainability through digitalisation. We provided recommendations for policy and managerial levers for socio-ecologically sustainable supply chains, such as putting a stronger focus on activating first-tier suppliers (in China) for collaboration on sustainability with second- and third-tier suppliers. The study served to reveal similarities and differences in perspectives between buyers and suppliers across different world regions, and linked isolated debates in the development economics and business science literature on the nexus between the economic benefits of value chain participation and environmental sustainability.

The third study investigated how far the degree of industry 4.0 in sectors is linked to energy consumption and energy intensity of industry sectors in China, and thus how much it may impact the sustainability of industry in the country. We conducted a panel regression analysis examining energy consumption, energy intensity, and the degree of industry 4.0 (as approximated by robot and patent data) in ten Chinese manufacturing sectors from 2006 to 2019. The results indicated that there was no overall significant association between the degree of industry 4.0 and energy use and energy intensity in manufacturing sectors in China. A negative correlation between industry 4.0 and energy intensity could be found for highly digitalised sectors, supporting the finding from earlier studies that digitalisation can have an energy-intensity reducing effect in technology-intensive sectors. A positive correlation between industry 4.0 implementation and energy use could be found for low-energy sectors, in line with the notion that digitalisation itself requires energy, e.g. due to automation in previously labour-intensive sectors. Based on the quantitative analysis, the study discussed industry and policy options to address energy use on the level of manufacturing sectors, highlighting risks for rebound and international relocation through industry 4.0. The contribution of the third study was its quantitative perspective on the development of industry 4.0 and energy consumption in ten manufacturing sectors in China, in contrast to the previous two qualitative studies. Rather than relying on traditional indicators of digitalisation (broadband coverage, internet users), we used industry-specific indicators aimed at industry 4.0, namely patents and robots. We also added to the debate by arguing that previous studies on digitalisation and energy indicators have made important omissions, which may have led to overly optimistic outlooks on the effects of artificial intelligence, industry 4.0, and digitalisation in some previous studies in the Chinese context.

When considering the results of all studies, I found that expectations and assumptions of positive potentials were more prevalent than concerns about the possible negative effects of digitalisation on the environment in all three studies, pointing to a rather technology-optimistic perspective on digitalisation in industry among actors. The majority of policy documents and scientific studies start their argumentation or modelling from the assumption that digitalisation entails efficiency gains, and explicitly or implicitly express that these efficiency gains are associated with benefits for the environment. Moreover, the levels of digital maturity on the country, sector, supply chain and firm levels appeared to have an influence on the relationship between digitalisation and sustainability in industry in all three studies. In all studies, the differentiation between direct and indirect environmental effects of digitalisation emerged as a useful analytical lens for my research. The awareness, definition, measurement, and management of environmental effects (what, how, by whom), particularly rebound effects, emerged as central challenges to understanding and enhancing environmental sustainability of digitalisation in industry in each of the contexts analysed.

What follows from these observations? In the next section, I discuss the individual studies' findings against the background of my overarching research questions regarding the opportunities, risks, and fields of action for environmental sustainability and digitalisation in industry.

6

Discussion

In this thesis, I asked three overarching research questions: 1. What are the expected and observed effects of digitalisation in industry with respect to environmental sustainability, considering perspectives of policy makers and industry representatives, as well as statistical evidence, in the Global North and South? 2. Linking the empirical results, which opportunities and risks arise for environmental sustainability through digitalisation in industry? 3. In light of these opportunities and risks, what are potential fields of action for promoting more environmentally sustainable (digitalised) industries through politics and industry? I have answered the first overarching research question with the results of my three studies. I answer the second and third question in the subsequent two sections by synthesising the results of these three studies (see also section 1.6 on the research design).

6.1 Opportunities and risks for environmental sustainability through digitalisation in industry

To synthesise my research findings, I have organised the discussion alongside a framework which differentiates between three analytical levels, namely the macro (international, national), meso (sector, supply chain) and micro (firm) level and two argumentative levels, namely, risks and opportunities of digitalisation in industry for environmental sustainability. The differentiation into macro, meso and micro level has previously been used in the debate around information systems and sustainability (Adamik and Sikora-Fernandez 2021; Melville 2010; Trevisan et al. 2023). The empirical results of my studies contribute insights at different levels of the framework. At the micro level, my second study offers insights into electronics firms' perspectives. At the meso level, my second study offers insights into the electronics supply chain. My third study offers insights into manufacturing sectors in China. At the macro level, my third study contributes insights into national-level implications for China. The first study contributes insights into national level policies. The discussion within this analytical and argumentative structure is summarized in Table 23.

Level	Study	Risks	Opportunities
Micro	2	Fostering digitalisation without considering its direct environmental effects Ignoring firm-level digital rebound	Steering digital technologies' efficiency-enhancing potential towards the reduction of energy and material use in industrial products, processes and systems Transforming to sustainable business models through digital technologies
Meso	2 and 3	Enhancing efficiency of unsustainable production patterns, supply chains, and sectors Outsourcing environmentally harmful industrial activities and sectors to countries with higher pollution intensity Generating sector- or chain-wide rebound	Setting framework conditions to incentivise or oblige sustainable digital innovation and digital environmental upgrading in supply chains and sectors Focusing digital innovation research on high environmental leverage sectors/supply chains (e.g., with high energy intensity)
Macro	1 and 3	Harnessing digitalisation primarily as a driver of economic growth Assuming that digitalisation will automatically reduce environmental degradation over time through technological progress Generating macro level rebound	Framing and designing digitalisation around the narrative of less energy- and resource-intensive development paths

Table 23: Synthesis of opportunities and risks of digitalisation in industry on the micro, meso and macro levels

6.1.1 Micro level

Risks

At the micro level, there is a risk in promoting digitalisation within firms without considering its direct environmental effects. As a consequence, hardware- and software-related negative environmental effects may overcompensate the potential environmental benefit generated by digitalisation. As I found in my second study, the interviewed firms that considered implementing digital technologies to improve their sustainability performance, did not appear to consider the direct environmental effects of the digital technologies themselves although the production of hardware and software, for instance, is a large contributor to resource and energy consumption in the technology lifecycle (Bull and Kozak 2014).

Regarding hardware, "green ICT" is discussed in the academic literature and mentioned in policy documents (study 1) to reduce the environmental footprint of digital technologies (e.g., related to material extraction) (Ozturk et al. 2011; Peng 2013; Verdecchia et al. 2017), but none of the interviewed firms mentioned green ICT measures as part of their considerations in digitalisation processes. One reason for low private-sector awareness of the topic may be that there are few companies that produce certified green ICT, and even fewer that cater to the industrial sector. There is also still too little insight into non-energy-related environmental effects of software and hardware (Bergmark and Zachrisson 2022). The increasing demand for materials in the transformation to industry 4.0 combined with the lack of sustainable hardware alternatives for industrial companies will further exacerbate environmental degradation in the producer/source countries (European Commission 2020b). Moreover, supply chain dependencies on countries such as China (Rabe, Kostka and Smith Stegen 2017), which provides 98 % of the EU's rare earth elements (European Commission 2020c), may result in supply interruptions for firms and additionally create political dependencies. Regarding software, when asked about the expected effects of the use of digital technologies, interview partners did not mention software-related sustainability risks. Again, private-sector perception does not seem to mirror the academic literature, which highlights several software-related sustainability risks, e.g. risks through obsolescence of hardware through software (Sissa 2013), and the use of increasingly computing-intensive software, such as artificial intelligence which is considered a key technology for industry 4.0 (Shankar and Reuther 2022). Such risks may be overlooked or neglected at the firm-level when conceiving digitalisation measures.

There is also a risk that firm-level digital rebound effects are neglected. My second study showed that many of the digitalisation measures suggested by the interview partners to improve sustainability (such as transport-related optimisation) carried a risk of rebound effects, but that these rebound effects were currently being ignored or overlooked. Rebound effects can take the form of direct and indirect rebound effects (Berkhout, Muskens and Velthuijsen 2000). Direct rebound effects occur when digital technologies result in efficiency gains, for instance, in energy and material use, which in turn yield cost savings. These savings may then be reinvested into the cheaper input, thereby (partially) offsetting or even over-compensating for the sustainability gains from digital technologies. Indirect rebound effects occur when the cost savings are reinvested into other inputs and activities, potentially with an adverse impact on the environment. The rebound effect might substantially reduce or even over-compensate expected sustainability gains from digital technologies ("backfire effect") (Widdicks et al. 2023), as I showed through several examples in my studies.

Opportunities

However, there are also opportunities to improve environmental sustainability in industrial firms, when digital technologies' efficiency-enhancing potential is steered towards the reduction of energy or material use in industrial products, processes, and systems (positive indirect effect) (Hilty 2005, 2008). In my second study, I elaborated on several cases of "sustainable digital innovation" in the fields of environmental data analysis, renewable energies and material circularity, where digital technologies may bring sustainability benefits if adequate framework conditions are in place. The analysis, however, also showed that several of the examples mentioned by the interview partners had not yet been implemented or had not been shown to deliver measurable sustainability benefits. Thus, their overall impact on environmental sustainability in firms, including compared to more environmental innovation not relying on digital technologies, remains to be seen in practice, as is the case for sustainable business innovation more generally (Bocken and Short 2021).

Another opportunity discussed in the literature is the possibility to transform companies' business models to sustainable business models through digital technologies (Böttcher et al. 2023; Brenner 2018). It is suggested that digitalisation helps to offer functionality instead of physical goods and build on peer-to-peer platform organisation. While this idea is appealing in theory, my second study did not indicate that businesses were considering a more profound sustainability transformation of their business models through digitalisation (yet). A transformation to peer-to-peer manufacturing in the electronics industry, for instance, may be difficult given the current organisation of supply chains involving thousands of suppliers of electronics components, distributed across the globe. Economies of scale put competitive pressure on those companies that may want to change their business models. In the short-term, it thus seems unlikely that a significant share of companies will be able to switch to sustainable business models through digitalisation, but it may be an orientation for medium- and long-term goals.

6.1.2 Meso level

Risks

At the meso level, there is a risk that digitalisation contributes to increasing the efficiency of existing unsustainable supply chains, and sectors. Efficiency gains and spillovers of (digital) technological innovation may occur in any field and thus also benefit environmentally harmful activities, such as oil exploration (GPAI 2021). This raises the bar of competitiveness for more environmentally beneficial value creation, such as renewable energy development, and fortifies path dependencies, e.g., discussed in the context of "carbon lock-in" (Unruh 2000). In my second study, for instance, one interview partner mentioned that digital technologies now allow for the prediction and setting of trends and production of specific car colours to meet customer demands in the coming season. Companies may produce the anticipated products with the risk that these products will fail, or with the expectation that another colour trend can be set next year, increasing incentives for (over-)consumption and production and associated resource use. Similar risks arise through the increased velocity of changes in products, and the possibility of personalisation and customisation of products (Watanabe et al. 2021). Overall, these digitalisation-related advancements often create economic benefits, but increase the number of products sold, reduce the time these products are used, and reduce reusability of customised products (Braccini and Margherita 2018).

Another risk at the meso level associated with digitalisation in industrial supply chains is the relocation of production activities (Butollo 2021), which enables the outsourcing of environmentally harmful activities. As I discussed in my third study, digitalisation can make it easier for firms to outsource their polluting industrial activities to countries with lower environmental standards and higher pollution intensity in the supply chain (see discussions about "carbon leakage" and "pollution havens" (Cai et al. 2018; Grubb et al. 2022)). I also showed that previous statistical studies have often neglected the possibility of relocation of pollution related to digitalisation. For the example of China, I argued that due to a) digitalisation advancements in industry, making Chinese industry more competitive internationally, b) China's domestic net-zero target by 2060, and c) rising domestic labour costs, Chinese firms may increasingly outsource activities to countries with potentially lower environmental standards (Tracy et al. 2017). The Chinese Belt and Road Initiative, a large infrastructure project across the Eurasian continent, further facilitates the relocation of polluting activities to countries along the "new Silk Road" (Tracy et al. 2017).

Finally, similar to the micro level, a narrow focus on efficiency optimisation may result in meso level rebound effects. Taking the example of road freight transport from my second study, networked production across facilities and countries was reported by one interview partner as helping to optimise truck logistics routes. Optimised route and fleet planning leads to reduced costs for transport in the supply chain and higher fuel use efficiency. On the flip side, this may mean that certain logistics routes only become economically viable through digital optimisation, leading to the economic amortisation of intensifying the use of these routes and transporting additional products. In such instances, a rebound effect is likely. For example, in the context of Chinese road freight transport, an analysis of 31 provinces between 1999 and 2011 showed that the rebound effect generated through efficiency improvements and cost savings offset the majority of the expected energy reduction (Wang and Lu 2014).

Opportunities

On the other hand, an opportunity arises when framework conditions set by industry and politics foster sustainable digital innovation on the sector level and digital environmental upgrading in supply chains. When asked about the influence of digitalisation on green innovative ability, buying firms and suppliers in my second study indicated that they expected a positive effect (3.8, 3.3 out of 5 (very positive effect), for N=9, 8, respectively). Likewise, interview partners expected digitalisation to aid the transfer of knowledge in supply chains about the use of energy- and resource-efficient manufacturing technologies and processes (3.6, N =9; 4.2, N =8, respectively). Considering the finding that (existing) digital technologies are not yet fully exploited for the purpose of environmental sustainability, however, supply chains actors may need to adopt a socio-technical perspective on sustainable (digital) innovation in order to understand the human and organisational barriers to achieving the expected environmental goals in supply chains.

Moreover, my third study showed, that energy intensity in highly digitalised sectors is negatively associated with the degree of industry 4.0. This could indicate that digitalisation yields efficiency gains once high enough digital maturity is achieved, or once structural changes (changes in goods produced; outsourcing) have occurred in these sectors that lead to decreases in energy intensity. In both cases, a further scientific investigation and understanding of these effects may reveal existing potential to harness efficiency-increasing potentials and omit negative effects of industry 4.0 through political interventions. This will be particularly relevant for energy-intensive sectors and supply chains, such as non-metallic minerals, metals, and chemicals, that are not yet highly digitalised in China. Here, digitalisation could be used as a lever in the reduction of energy use (e.g., as investigated by SynErgie (2022) and UNECE and ESCWA (2022)) but also faces a high risk of rebound effects (Jin and Yu 2022).

6.1.3 Macro Level

Risks

At the macro level, there is a risk that digitalisation is primarily harnessed as a driver of economic growth through productivity increases in the economy and mainly result in increased value added, rather than facilitating the necessary sustainability transformation (WBGU 2019a). As shown in my first study, the majority of the policy documents that had initially been scanned (25 of 38) lacked any expectations regarding the effects of digital technologies on environmental sustainability of industrial development in the Global South, indicating that there is a lack of interest and/or awareness of the topic at the national level in the observed countries. Digitalisation is more typically framed and investigated as a driver of economic growth (Davies 2015; Ishida 2015; Niebel 2018; World Bank 2016). Economic growth, however, usually results in increased emissions (Aye, Edoja and Charfeddine 2017) and increased resource consumption (Bringezu et al. 2004), so there is a deep-rooted conflict in the growth-enhancing and ascribed sustainability-enhancing effects of digitalisation. Nonetheless, the policies analysed in my first study neither address nor resolve this trade-off. None of the policies give answers to the questions of how industrial development processes can be made environmentally sustainable, i.e., to “leapfrog” traditional industrial development and all its associated environmental problems (Geng and Doberstein 2008).

The assumption that digitalisation will automatically reduce environmental degradation can be linked to the economic discussion around the impact of technological change on the environment (EKC theory, see section 1.3). In my third study, I showed why this assumption is problematic. For Chinese manufacturing, I did not find an overall negative correlation between the degree of industry 4.0 and energy use, i.e., industry 4.0 innovation was not associated with decreasing energy use in manufacturing. I showed that empirical results in previous studies on the decoupling effects of digital technologies and environmental impacts in China can often be linked to limitations in the empirical studies such as omitting international outsourcing dynamics, and neglecting systemic interactions (Zhang and Wei 2022). For instance, micro and meso level efficiency increases may lead to macro level growth of energy consumption. Thus, as these limitations affect the credibility of the proclaimed *causality* between digitalisation and reduced environmental impact in some previous papers, it may be unjustified to place high expectations on the future environmental benefits of digital technologies on the grounds of such methodologically limited quantitative analyses. Methodological limitations in existing studies have recently also been criticised by Coroamă et al. (2020) and Freitag et al. (2021). On a more general note, some recent studies of the EKC theory using consumption-based approaches, that capture environmental impacts occurring in other countries for domestic consumption, do not generally find a significant decreasing relationship between income, related technological change and environmental degradation (Ansari 2022; Dorsch and Kirkpatrick 2021; Frodyma, Papież and Śmiech 2022) – which speaks against the hypothesis that technological change will decrease global environmental pressure over time as global income increases.

Caution regarding expectations of the positive effects of digitalisation at the macro level may also be warranted, as there is a risk of digital rebound (Bergman and Foxon 2022; Brockway et al. 2021; Coroamă and Mattern 2019; Gillingham, Rapson and Wagner 2016). As discussed in my third study, when digitalisation promotes energy efficiency on the macro level it can result in direct rebound effects, such as increasing energy demand through economic growth outpacing efficiency gains, and indirect rebound effects, such as when the resources saved through decreased energy prices are invested in other, more environmentally harmful activities. In the case of China, overall energy consumption in manufacturing has not declined despite increases in energy efficiency. I argued that the rebound effect may not be a potential side effect of (energy) efficiency increases but may actually be a default consequence, since efficiency increases *cause* growth (Sakai et al. 2019). If rebound effects are enshrined in efficiency-driven economic development, then prospects of an absolute decoupling of economic growth and environmental degradation through (digitalisation-related) efficiency improvements would be significantly dampened. Digital rebound effects may even lead to backfire effects, i.e., the compensation of all of or more than digitalisation's efficiency gains.

Opportunities

Taking into consideration the described risks, there may be an opportunity to shape the visions, norms, and narratives of digitalisation towards promoting "provisioning systems" in the Global North and South, such as outlined conceptually by Fanning, O'Neill and Büchs (2020), O'Neill et al. (2018) and others. The basis of such an alternative approach to digitalisation could be: 1) a strong sustainability concept, that does not view natural resources as substitutes but as complements of other forms of capital (Daly 1995) and accepts planetary boundaries as boundary conditions of societal activities (Rockström et al. 2023), and 2) a priority on absolute reduction targets and sufficiency-oriented (instead of efficiency- and consistency-oriented) agendas (Ferreboeuf et al. 2020; Haberl et al. 2020; Kunkel and Tyfield 2021; Li et al. 2021; Santarius et al. 2022).

Some policy visions, analysed in my first study, contained hints suggesting alternative policy visions. For example, digitalisation in industry in China is portrayed as an enabler of a knowledge-based economy and an "ecological civilisation", in line with the concept of green, high-quality development (Li et al. 2019). However, the concept can be viewed rather as an ideological framework for an alternative Chinese approach to sustainable development (Gare 2021; Goron 2018; Hansen, Li and Svarverud 2018; Tracy et al. 2017), and thus lacks transformative aspects needed for a renunciation of resource-intensive development pathways and has not delivered low environmental impact growth to date (Chen and Golley 2014). In Thai and South African strategies, the concept of a knowledge-based economy also emerged in the context of providing a path to more environmentally friendly economic systems. However, the concepts remained vague and policies did not outline any specifics on how to arrive at such a system. To ensure environmental justice and buy-in, the heterogeneous needs of different countries with different preconditions will need to be recognised in alternative policy visions of digitalisation aligned with less energy- and resource-intensive provisioning systems. In particular, these visions will need to compete with the prevalent imperatives of industrial growth for prosperity, as advocated by the UN (including in the SDGs) and World Bank, among others (Hallward-Driemeier and Nayyar 2017; Kiely 1998; Salazar-Xirinachs, Nübler and Kozul-Wright 2014; UNIDO 2020).

In conclusion, at all levels, a narrow focus on efficiency through digitalisation in industry can lead to neglecting digital technologies' environmental footprint, creating digital rebound effects and accelerating unsustainable industrial production patterns. Conversely, opportunities exist in harnessing micro and meso level changes in industrial products, processes, and systems through sustainable digital innovation given ambitious absolute reduction targets incorporating a strong sustainability concept.

6.2 Fields of action in politics and industry

In this section, I go beyond my studies' findings to propose several fields of actions and measures, mainly in politics and industry, to mitigate the identified risks and foster the identified opportunities on each of the three levels of analysis (micro/meso/macro). I differentiate between fields of action on the direct and indirect effects, as first introduced in my first study (see Figure 3, in section 2.2). These fields of action are not an exhaustive list but represent a starting point for further discussion.

Direct environmental effects	**Indirect environmental effects**
Micro - **Who?** Industrial firms using digital technologies	
Identifying, (measuring,) and mitigating environmental effects of digital technologies	
• Using second-hand, remanufactured or certified hard- and software • Switching to renewable energies, ideally adding capacities • Offsetting digitalisation-related environmental burdens	• *Either* identifying, measuring and reducing indirect environmental effects, *or* focusing on broader sustainability management and goals in the company and switching to more sustainable business models • Employing digital sustainability expert to identify behavioural changes associated with digital technology use, upskill personnel regarding (digital) sustainability and participate in (transdisciplinary) research projects
Meso —**Who?** Policy makers, standard setters, industrial associations, ICT sector	

• Establishing or tightening sustainability standards and regulations covering the environmental effects of the ICT sector
• Better aligning regulations covering direct environmental effects
	• Improving and enforcing environmental policies in non-ICT sectors and supply chains by
	  – combining circular economy and supply chain sustainability policies
	  – implementing safeguards against rebound effects
	• Strengthening collaboration on environmental data and knowledge sharing (cross-sectoral, cross-country)

Macro — **Who?** Policy makers, international organisations	

• Developing and enacting national policies to implement the recommendations and goals set by standardisation bodies on direct effects
• Green(er) ICT in public procurement
• Proliferating (digital) sufficiency as guiding policy principle
	• Aligning digital and industrial policies with the goal of a green transformation
	• Co-developing feasible policy visions for the Global North and Global South:
	  – environmental sustainability as a primary objective of digital technologies' application in policies; shift to post-growth, degrowth
	  – abandoning "pollute first, clean up later" principle, adopting low-environmental-impact society and economic models
	• Reducing rebound through absolute caps on environmental indicators and sufficiency orientation in policies, and systemic approaches

Table 24: Fields of action to steer environmental effects of industry 4.0 towards environmental sustainability.

6.2.1 Micro level

Direct environmental effects

To address direct environmental effects on the micro level, such effects should be identified, (measured) and mitigated by industrial firms using digital technologies. There is information on procedures available from various sources, such as scientific publications, standardisation bodies' and public institutions' guidelines.[16] Regarding **energy consumption** in firms, following standards such as ISO 50.001 can allow the identification of energy savings measures (McKane et al. 2009) with respect to digital technologies. Regarding **hardware**, procuring second-hand or remanufactured hardware may currently be the most environmentally friendly options of procuring hardware. Additionally, companies can follow best practices to deal with e-waste (Vishwakarma et al. 2022). Regarding **software**, firms can use environmentally certified software, contribute to open-source projects, support research and raise awareness around environmental effects of software in the firm, such as through the "Software Sustainability Awareness Framework" workshop procedure presented by Penzenstadler et al. (2020). Further actions on the firm level include switching to renewable energies, ideally adding capacities, complemented by offsetting any remaining (digitalisation-related) environmental burden (Engler et al. 2023).

Indirect environmental effects

To address indirect environmental effects of digital technologies, one option would be to identify, and measure such effects through methods like life cycle analysis (Open LCA undated), partial footprint analysis, dynamic systems modelling, and agent-based modelling, among other means (Bieser and Hilty 2018). ITU's standard L.1480 provides a guideline for measuring the indirect effects of ICT in other sectors (ITU 2022). However, not only energy and emissions, but also a broader set of sustainability indicators should be considered, taking into account recent developments concerning the overshooting of planetary boundaries (water, land, chemicals, etc.) and their attribution to the micro level (Ryberg et al. 2018).[17] On the basis of direct and indirect environmental effects, a net measurement of the environmental effect of digitalisation measures on the micro level could be established (ITU 2022). This net measurement could inform decision-making about whether to pursue a specific digitalisation initiative in the firm, evaluated from an environmental sustainability point of view.

Challenges in measuring and reducing indirect effects, however, exist regarding a) the determination of the relevant system boundaries, obtaining data, and establishing causal links between the suspected cause (use of digital technology) and the environmental effect (or progress towards environmental objectives), b) the lack of political and economic incentives to measure and reduce such effects. I suggest two approaches to addressing these problems.

The first approach would be to use and improve existing procedures, drawing from scientific research to approximate the indirect environmental effects of digital technologies. Beyond ICT

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[16] Related publications include information criteria for energy and resource-efficient software (Kern et al. 2018; Naumann et al. 2021), data centres (Gröger et al. 2021; Schödwell and Zarnekow 2018), general guidelines and standards for carbon emission measurement and mitigation along the supply chain (BMUB and UBA 2017; CDP 2023) and broader sustainability (reporting) guidelines, e.g., GRI (GRI 2023), ISO 14000 (environmental management standards) and EMAS (European Commission 2011)

[17] As an approach to achieving a circular economy, for instance, Rossi et al. (2020) nine environmental indicators on the micro level: reduction of raw material, renewability, recyclability, reduction of toxic substances, reuse, remanufacturing, refurbishment, product longevity, stakeholder structure and diversity. The contribution of digital technologies to achieving a circular economy (Bressanelli et al. 2022) could be measured qualitatively or quantitatively.

specific procedures, firms could, for instance, build on the theory, concepts, and implementation guidelines behind measuring supply chain emissions according to the Greenhouse Gas Protocol, with a focus on scope 3 emissions (GHG Protocol and Carbon Trust 2013; Green Software Foundation 2023) [18], since they are the most similar to digitalisation's indirect effects. The second approach would be to refrain from measuring indirect effects of digital technologies in detail and embed the optimisation of digital technologies' environmental effects within firms' broader (sustainability) management. Given the complexity and potential cost of establishing a net environmental assessment of digital technologies in the firm, it could be a pragmatic rule of thumb to ask whether the introduction of a digitalisation measure serves the more far-reaching sustainability goals of the firm, e.g., those related to established reporting indicators for environmental sustainability at the firm level.

If firms seek to adopt more ambitious sustainability understandings, the scientific literature provides guidance to alternative business approaches Khmara and Kronenberg (2018), for instance, suggest following seven principles to translate degrowth to the firm level. These principles mainly focus on switching the company's business model to more sustainable business models, such as sufficiency-oriented, circular, common good-oriented, not-for-profit, from net-zero to environment-positive impact business models (Bocken et al. 2014; Böttcher et al. 2023; Schröder et al. 2019; Silva et al. 2019). Based on the principles, firms can ask whether and how specifically digitalisation measures can enable or may hinder the necessary shifts. If the aspired goals could equally be achieved without digital technologies, this option may be the more sustainable option, given direct negative environmental effects of digital technologies.

Finally, a (digital) sustainability expert within the firm could support both approaches, i.e., sustainability assessments of digitalisation measures and identification of the synergies between digitalisation measures and the overall sustainability strategy of the company. Collaboration with NGOs and diverse practitioners in the company, e.g., through transdisciplinary research projects, would also be useful, as leveraging digitalisation for sustainability in industry is found to require interdisciplinary teams with specific competencies and values (e.g., integrative leadership, establishing a common language, broad views on the issues raised, and building a team consisting of specialists with the required competencies) (Lacy, Arnott and Lowitt 2009; Podgórska 2022). For example, by organising and conducting workshops with employees and external stakeholders, the expert can help sensitize the firm to behavioural changes associated with digital technologies which may lead to unintended rebound effects and shift the values and priorities of the workforce towards sustainability.

6.2.2 Meso level

Direct environmental effects

To reduce direct environmental effects on the meso level, i.e. in the ICT sector, environ-

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[18] In supply chain emissions accounting, all emissions that are directly related to the firms' own activities and energy demand are scope 1 or 2 emissions. Scope 3 emissions occur in the firms' supply chain and comprise emissions of purchased goods and services, and direct use-phase emissions of sold products (over their expected lifetime), among other things (GHG Protocol and Carbon Trust 2013).

mental sustainability standards[19] and regulations covering the planetary boundaries framework (Bergmark and Zachrisson 2022) should be established or tightened, as long as there are no macro level regulations that also cover the ICT sector, such as a global carbon constraint (Freitag et al. 2021). Life cycle analysis approaches to studying the direct environmental effects of ICT should be supplemented by environmentally extended input-output methodologies to include supply chain effects more comprehensively (Freitag et al. 2021).

Numerous interacting regulations related to the direct environmental effects of digital technologies should be better aligned and enacted. For instance, the Ecodesign for Sustainable Products Regulation, the Conflict Minerals Regulation, the EU proposal for battery regulation, the Directive on the Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment or the Directive on Waste Electrical and Electronic Equipment (WEEE) all include crucial elements to improve digital products' eco-design, increase their lifetime and foster reduction, recycling, recovery, and reuse of WEEE. The implementation of the EU's and China's circular economy plans could function as umbrellas to merge these elements and create a coherent policy framework for electronic companies to reduce their environmental impact (Pan, Wong and Li 2022).

Indirect environmental effects

To address the indirect environmental effects on the meso level, several (existing) environmental strategies, standards, and regulations need to be implemented recognising the role of digital technologies, while containing sector- and chain-wide rebound effects (of digitalisation). Three policy fields in this context seem particularly relevant. First, on the sector level, environmental policies with safeguards against rebound effects should be implemented. The central questions of policy debates about digitalisation in this regard should be focused on how digital technologies can aid in reducing energy and resource consumption a) considering behavioural adaptation and rebound effects (Bergman and Foxon 2022; Pohl and Finkbeiner 2017) and b) compared to a counterfactual scenario without digital technology use (Achachlouei and Hilty 2015). For energy, measuring standards for energy savings on the sector level and stricter energy efficiency measures[20] should be combined with absolute energy demand reduction targets, which currently receive little attention (Bobrova et al. 2023). Within these framework conditions, the uptake of specific, environmentally beneficial digital solutions can be fostered through government-business collaborations, as in the case of China (Kostka and Zhang 2018), long-term funding schemes for academic-industrial partnerships, and the standardisation of industrial data, among others (Teng et al. 2021).

Second, circular economy and supply chain sustainability policies should be combined more stringently (Zeng et al. 2017) and implemented across sectors and countries in industrial supply chains, to avoid the mere relocation of environmental burden. The EU's proposed "digital product passport" (DPP) as a tool to provide actors with information on the embodied environmental impacts of products and services along the value chain is a positive step into this direction. By

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[19] For instance, the ITU Telecommunication Standardization Sector (ITU-T) and the European Commission continuously develop standards covering ICT's environmental impacts (European Commission joinup 2022; ITU-T 2012).

[20] Examples for such energy efficiency measures are the EU energy efficiency directive (European Parliament 2012), and the Chinese energy intensity reduction goals (Shuai Shao et al. 2019).

2024, the DPP is expected to be introduced in at least three value chains[21], but more value chains should follow suit. Moreover, the focus on industry stakeholders and business-to-business relationships should be strengthened. The “Corporate Sustainability Due Diligence Directive” as well as the “Corporate Sustainability Reporting Directive” proposals from 2022 are two additional elements of linking supply chain and circular economy efforts. The implementation of the reporting directives is expected to proliferate the digitalisation of sustainability information (European Commission 2023). However, they are limited in scope, lack enforcement mechanisms (Bossut et al. 2021; Smith-Roberts 2022) and reduction targets. Thus, their scope needs to be extended, and reduction targets have to be put in place, e.g., the obligatory reporting and annual reduction of environmental effects in line with the planetary boundaries framework.

With respect to China, circular economy and supply chain legislation are also treated separately. Circular economy policies have existed for many years (NPC 2018; Yuan, Bi and Moriguichi 2006), aiming to foster information exchange among companies and sectors (Sheng et al. 2022). However, actual implementation of the circular economy is still found to be low, and Chinese authorities are urged to promote circular economy reforms, pilot projects, and demonstration zones (Fan and Fang 2020). Similarly, there does not seem to be a coherent green supply chain management system in China. Sheng et al. (2022) find it to be regulated by numerous entities (six ministries, one commission, and one Committee) with only 4 of 100 different policies focusing on environmental information and disclosure. The authors conclude that establishing an “environmental information disclosure platform” and using big data to facilitate public participation in the construction of such an information platform (Sheng et al. 2022) may help to foster green supply chain management in China.

Third, collaboration on environmental data and knowledge sharing between the EU, China, and other trading partners should be strengthened to overcome common challenges such as the coherence between, and enforcement of, circular economy and sustainable supply chain policies in both jurisdictions. Cross-country (digital) information sharing and the establishment of accounting platforms for sustainability information and risk management should be extended, which can then also be used by firms internationally for reporting and improving sustainability indicators. For example, the “Shared Environmental Information System (SEIS)”, implemented across several EU countries by the European Environment Agency in 2008, integrates numerous environmental information sources[22], and the Global Earth Observation System of Systems (GEOSS) which connects earth observation data systems from across the globe (GEO 2023) and makes them available in machine-readable format to multiple users through open software (EEA 2020). The Chinese Institute of Public & Environmental Affairs (IPE) provides a data collection of information from local governments and enterprises on environmental indicators (IPE 2023). Ensuring interoperability and interaction between such initiatives in the EU and China will enhance the comprehensiveness of environmental information from industrial supply chains and facilitate environmental assessments by companies operating in different countries.

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[21] The suggested list includes textiles, construction, industrial and electric vehicle batteries, electronics, packaging, and food (European Commission 2023)

[22] Among the integrated data sources is the Copernicus programme, which also offers climate data for businesses (Copernicus 2023).

6.2.3 Macro level

Direct environmental effects

To address direct environmental effects, national and international policies need to develop and effectively enact regulations, and goals set by standardisation bodies. For instance, ITU members committed to increasing the global e-waste recycling rate to 30 % by 2030 (ITU 2018b) and to implementing measures to establish an e-waste management framework (ITU-T 2020). Effective implementation of e-waste legislation, however, is still found to be low (Shahabuddin et al. 2023). To extend debates to the global context, demands for effective policy implementation should be negotiated in international forums, such as the UN Global Digital Compact or the OECD/G8 negotiations on the digital economy. Furthermore, governments can promote the provision and adoption of more sustainable ICT products through the mandatory public procurement of Green ICT, for which the ITU and others provides guidance (Gröger 2020; ITU 2012) and through supporting industry efforts by funding public-private research partnerships in more environmentally-friendly approaches to ICT manufacturing. A Fraunhofer research project, for instance, explores more environmentally friendly cleaning technologies in microchip production, reducing the amount of chemicals used (Fraunhofer IPMS 2023). Finally, a more causal treatment to address the problem of energy and resource use of digital technologies would be to promote digital sufficiency as a guiding policy principles, that is, using as many digital technologies as necessary but as few as possible to reduce the amount of digital products produced in the first place. This, however, would require a political commitment to the notion that more digitally advanced systems are not always better than low-tech or analogue systems (Ferreboeuf et al. 2020; Santarius et al. 2022).

Indirect environmental effects

To address indirect effects, digital, industrial, and other related policies have to align with the greater goal of a green transformation. The primary objective of the application of digital technologies in these policies would be to support the transition to an environmentally sustainable economic system which manages to stay within planetary boundaries and provide a good life for all (O'Neill et al. 2018; Rockström et al. 2023). Such a system does not currently exist anywhere in the world (O'Neill et al. 2018). To construct a vision of digitalisation in the context of a profound green industrial transformation, it may be a starting point to analyse systematically which indicators will define a future sustainable economic system within which the costs and benefits of human well-being and environmental protection are linked. Starting points for such indicators include the planetary boundaries/pressures adjusted Human Development Index (UNDP 2021; Zhang and Zhu 2022) and the determination of planetary boundaries-compatible national/industry-sector shares of environmental resources (Hjalsted et al. 2021; Li et al. 2021). It could then be analysed whether and how digitalisation may hinder or help the achievement of the defined socio-environmental goals. Existing macro level sustainability scenarios such as the shared socio-economic pathways used in the IPCC reports could be used to illustrate the opportunities and risks associated with digitalisation and provide further operationalisable sustainability goals with respect to (existing) scenarios for digitalisation (Creutzig et al. 2022; WBGU 2019a), differentiated across world regions.

Where digitalisation is expected to make positive contributions, its values should be shifted from technology- towards human-centricity, environmental sustainability and regeneration (Moreno and Charnley 2016; Xu et al. 2021). Governments' commitment and communication is an important driver in this shift. In the Global North, (digital) sufficiency and digitalisation with the objective of transitioning to a post-growth/de-growth/growth-independent economy should be prioritised, as suggested by Hickel (2018). In hitherto less industrialised regions, digital and industrial policies should aim for the least energy- and resource-intensive pathways to provide well-being to citizens, with specialisation in sectors in which countries have environmental comparative advantages (Peters and Hertwich 2008). They should be conducive not only to the low-carbon economy (Ren et al. 2014) but to the low environmental impact economy, e.g., the decarbonised energy sector (Kriegler et al. 2014), (waste)water treatment (Yenkie 2019), the (sufficiency-based) circular economy (Bocken, Niessen and Short 2022), educational services, e.g., in education for sustainable development (O'Flaherty and Liddy 2018), and deep transformation. For instance, Bataille et al. (2018) suggest stakeholder-driven national pathway processes in energy-intensive industries to manage the industrial transformation at minimum social cost. Appendix A summarises some additional suggestions for approaches to enhancing the environmental sustainability of the economy discussed at the international level, which may support the envisioned industrial transformation.

To summarise, Figure 19 serves as an illustration of the interplay of measures for more sustainable (digitalised) industries suggested in this section. The figure is based on a recent conceptualisation by Schaltegger et al. (2022) and highlights the need for top-down and bottom-up action in the design of a more sustainable (digitalised) industrial system.

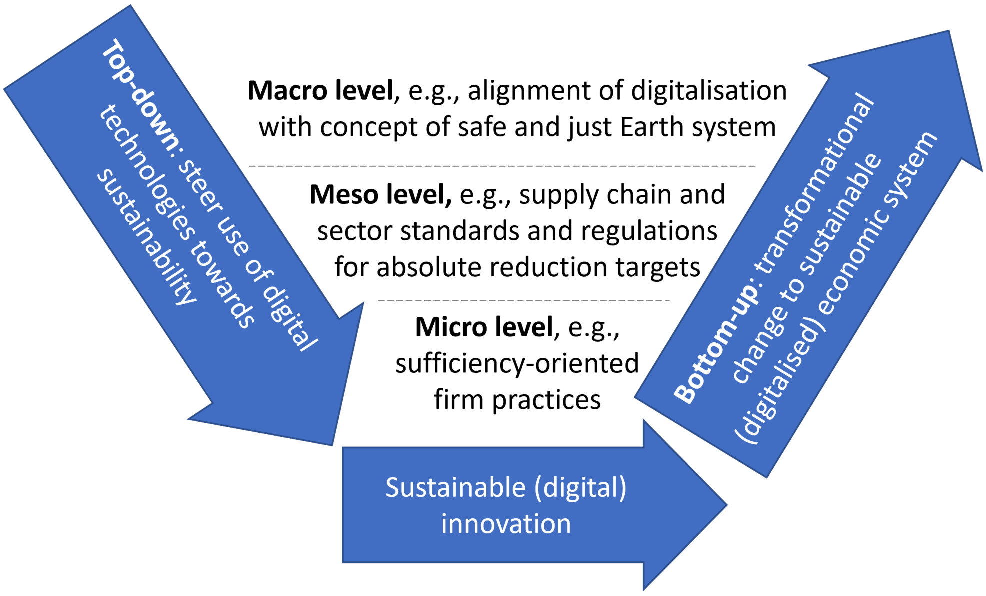

Figure 19: Illustration of the interplay between the suggested measures for more sustainable (digitalised) industries on the three levels of analysis, source: own elaboration based on Schaltegger et al. (2022)

6.3 Limitations

The nature of this dissertation, covering various contexts and incorporating various disciplinary perspectives, methodologies and foci, has resulted in several limitations. First, the depth of coverage for each topic addressed in my studies is limited due to the choice to address multiple contexts. A narrower focus of analysis could have led to a more comprehensive theoretical and empirical review of each topic. The approach I chose required an immersion into different scientific fields, literatures, and methodologies, i.e., policy analyses for the first article, interview methods and supply chain literature for the second, and econometric analysis of sectoral data for the third. Each shift in focus also required the adoption of new vocabulary, concepts, conventions, and definitions, among other aspects. The conclusions I was able to draw are broader instead of highly specific. I believe that this approach was justified, however, since one of my critiques of the research field consisted in siloed disciplinary knowledge creation and the omission of systemic interdependencies, which currently impede practical political and private sector action for more sustainable (digitalised) industries.

Second, the rapidly evolving field of digitalisation in industry at the intersection with sustainability research lacks an established scientific community, literature, theories, and methods. Therefore, I had to develop individual theoretical approaches and choose exploratory study designs. This resulted in difficulties in identifying journals and reviewers matching the chosen research focuses of the three studies. For instance, the use of patent data which is common in innovation research, is not widely used in the field of digitalisation research, particularly regarding impacts of digital innovation on energy use in industry. To use patent data, I had to develop a research framework within which robot and patent data could be combined and seek a collaboration with a patent scholar and identify an interdisciplinary journal with interest in the econometric investigation of the intersection of innovation and energy in manufacturing sectors.

Third, each study had its own limitations that required individual reflection on appropriate measures to address them. Policy documents, for instance, only provide a limited view of the policy process and are drafted for public communication, potentially presenting a positive and optimistic picture of the country and policy field. This raises issues around the reliability of my results. In the case of interviews, the selection of the sample is critical, and in our study it was not possible to construct a representative sample due to the unavailability or lack of commitment from the majority of supply chain representatives we contacted, albeit in times of economic uncertainty in the Covid-19 crisis. This limits the generalisability of our results. On the other hand, statistical data has downsides, too, such as difficulties obtaining comprehensive time series data on industry 4.0 for longer time periods and establishing causality. By combining different methodologies in this dissertation, I was able to balance some of the individual limitations of each study and attain a more systemic understanding of the research field.

Finally, a more general challenge in research related to sustainability is normativity, potentially leading to researcher bias. I have outlined my normative position as a researcher in section 1.5, i.e., being interested in the transformation of industry towards more environmentally sustainable operations and viewing digitalisation as a socio-technical process. Making normative assumptions explicit allows the reader to evaluate the results of each study in light of these assumptions, which can be considered a remedy to the critique of normativity in sustainability science (Boda and Faran 2018).

6.4 Future research on digitalisation and sustainability

In light of the results and limitations of my thesis, several possible future research directions seem worth pursuing. I differentiate between future research topics related to direct and indirect environmental effects. With regard to direct environmental effects, opportunities and barriers to "green hardware" manufacturing could be examined, taking into account diverse sustainability parameters (energy, resources, water, land use, etc.). For example, the framework conditions (regulations, incentivisation) that need to be in place to mainstream more environmentally friendly sourcing of materials (preferably extracted from used products and e-waste) and to incentivise businesses to offer such solutions, including related software, to both private and industrial customers ("green industry 4.0") should be investigated. Moreover, the possible means of and need for regulation of (future) technologies' energy and material requirements should be investigated (e.g., in relation to more computationally demanding computing such as AI and quantum computing).

Regarding indirect environmental effects, the systemic impact of digitalisation in industry needs to be better understood, which will have multiple effects on the environmental sustainability of industry. The structural change associated with digitalisation, for instance, affects trade, composition of sectors, technological efficiency, and economic income/growth (Matthess and Kunkel 2020). These shifts shape the economic system's demand for environmental resources, e.g., through change in production patterns and consumption behaviours, but are barely understood and quantified, especially regarding environmental indicators beyond energy consumption. Trade-offs between different sustainability indicators may increasingly come to bear, for instance, when digitalisation leads to energy savings or social advancements (such as access to digital services) on the one hand, at the expense of materials for the production of digital technologies and biodiversity impacts associated with mining on the other hand.

More work is also needed to understand how more ambitious sustainability approaches (e.g., from efficiency to sufficiency) can be incorporated into digitalisation agendas at all levels, and which effects this has. For instance, the efficacy of policy measures aimed at promoting more sustainable digitalisation in different country contexts, including in the Global South, should be investigated and best practices identified. Through transdisciplinary research projects, researchers should actively contribute to bridging the science-practice gap in research around digitalisation and sustainability and co-create feasible sustainability solutions for the industrial sector. Specifically, collaboration between researchers, policy makers, industry associations, and firms on the exploration of incentives and measures for promoting digital sufficiency at the micro, meso and macro levels, on the sensitisation of practitioners in software and hardware development and regulation of its environmental effects, on understanding the tradeoffs of different sustainability dimensions (particularly social and environmental), and on co-developing visions of rebound-reducing, system-questioning digitalisation for sustainability should be pursued.

7

Conclusion

In this dissertation, I embarked on an exploration of the expected and observed effects of digitalisation in industry (industry 4.0) on environmental sustainability. I conducted three empirical studies utilising interdisciplinary methodologies. I discussed the risks and opportunities associated with digitalisation in industry for environmental sustainability on the micro, meso and macro level and ultimately recommended fields of action on each level.

From this endeavour, I draw a set of conclusions. First, digitalisation in industry will likely entail several effects, particularly growth effects, which tend to increase the environmental impact of industry. My actor-centred empirical analyses of the way that digitalisation is currently perceived and pursued gives rise to the concern that industry and politics mainly focus digitalisation measures on the maximisation of firms' value and economic growth. Digitalisation appears to be aligned with and strengthens today's unsustainable industrial system in terms of how firms mainly use digital technologies, how supply chains are organised, which expectations are held by actors regarding its effects and which values it ultimately delivers in the industrial system. While digital efficiency increases may contribute to a relative decrease in resource use (relative decoupling) in this system, as indicated for some sectors in my quantitative analysis and suggested widely in the literature, these efficiency increases are likely to cause rebound effects, on the micro, meso and/or macro level, which compensate a yet uncertain share of the expected efficiency achievements. Combining the actor-centred and quantitative perspectives, my studies do not indicate that the expected negative effects will be more than compensated by efficiency gains through digital technologies in industry. In view of yet unsaturated markets for industrial products, particularly in emerging economies, it is probable that the industrial output of goods and services will grow more rapidly than technology-driven environmental efficiency. Thus, as the economy continues to grow, environmental burden continues to grow.

Second, the systemic, socio-technical analysis in this dissertation also showed that digitalisation's environmental effects can be shaped by the organisations, humans and societal structures within which digitalisation is embedded. To start changing the way that digitalisation is pursued towards environmental sustainability requires considering the interactions between micro, meso and macro level. On each level, the framework conditions to transform industry (mindsets, regulations, incentives, ...) need to be created such that the technological potential of digital technologies for sustainability and actors' agendas are aligned. To overcome path dependencies and the push-back of industry interest groups in the system, social or socio-technical rather than technological innovations are needed.

Third, to initiate such innovations, societal actors in different capacities (from industry, science, politics, civil society), willing to work towards the necessary shifts, should engage in the process of co-creating solutions to the identified challenges. I suggested starting points for these solutions in section 6.2. Specifically, science and civil society should initiate transdisciplinary research projects with practitioners in politics and industry a) to build a shared understanding of the environmental risks of digitalisation to reduce these risks and b) to initiate transformative organisational changes in companies and on the sector/supply chain level towards sustainability (bottom-up). Policy makers need to negotiate and enforce limits on resource extraction and pollution, from the international to the community level, taking into account stakeholders' (often socioeconomic) concerns without being suffocated by particular groups' interests (top-down). A comprehensive political framework is indispensable to redirect industrial and political strategies from currently mainly exploiting digitalisation's economic benefits and industrial growth effects, towards achieving environmental objectives on the micro, meso and macro level.

Finally, as acknowledged throughout this dissertation, digitalisation affects more dimensions than environmental sustainability alone. Social justice, such as the fair distribution of incomes generated from digitalisation in industry, should be of high societal and political relevance. However, higher incomes usually manifest in higher consumption and higher environmental pressure (Jain and Jain 2020; O'Neill et al. 2018). The biggest challenge of sustainable digitalisation - the reconciliation of human and planetary well-being - is the central challenge of the Anthropocene. Our biggest opportunity lies in creating an upward spiral to turn not only digitalisation and our industries towards sustainability, but also society at large.

Appendix

Appendix A: Further sustainability goals

Below, I collected several sustainability goals not directly related to industry that may help to direct digitalisation in industry towards sustainability targets:

- implementing 100 % renewable energy systems before or by 2050 through national roadmaps (Jacobson et al. 2017; Teske 2019)
- enforcing international treaties on carbon pricing, tightening the EU ETS, accounting for international (relocation) dynamics through border adjustment schemes (such as CBAM) and carbon clubs, as well as strict environmental standards in international trade agreements (Jakob 2021)
- including additional sectors (cement, aluminium, and steel sectors) in China's carbon market (Asia Financial 2022; Nie et al. 2022)
- enforcing stricter obligatory environmental and social governance (ESG) and supply chain reporting (focusing on scope 3 environmental impact) (Hertwich and Wood 2018)
- greening the financial system, e.g., through green public investment, retirement funds, green central banking (Nick, Dikau and Volz 2021)
- protecting 30 % of the earth's global surface (Dinerstein et al. 2019)
- taking into account global biodiversity targets in business decisions (Smith et al. 2020)

Appendix B: Publication list

Kunkel, S., Schmelzle F., Niehoff S., Beier G. (2023). More sustainable artificial intelligence systems through stakeholder involvement? GAIA-Ecological Perspectives for Science and Society 2023 (32):64–70. https://doi.org/10.14512/gaia.32.S1.10 .

Kunkel, S., Terhorst, S., Beier, G. (2023). Digitalization and resilience of industry sectors: A descriptive analysis of the Covid-19 crisis in Germany. International Journal of Technological Learning, Innovation and Development, 15(1), 1. https://doi.org/10.1504/IJTLID.2023.10055714.

Kunkel, S. & Matthess, M., (2022). Industry 4.0 in sustainable supply chain collaboration: Insights from an interview study with international buying firms and Chinese suppliers in the electronics industry. Cleaner Logistics and Supply Chain 4, 100038. https://doi.org/10.1016/j .resconrec.2022.106274.

Kunkel, S., & Tyfield, D. (2021). Digitalisation, sustainable industrialisation and digital rebound–Asking the right questions for a strategic research agenda. Energy Research & Social Science, 82, 102295. https://doi.org/10.1016/j .erss.2021.102295.

Kunkel, S., & Matthess, M. (2020). Digital transformation and environmental sustainability in industry: Putting expectations in Asian and African policies into perspective. Environmental science & policy, 112, 318-329. https://doi.org/10.1016/j.envsci.2020.06.022.

Matthess M., **Kunkel, S.**, Dachrodt M.F., Beier, G. (2023). The impact of digitalization on energy intensity in manufacturing sectors – A panel data analysis for Europe. Journal of Cleaner Production;397:136598. https://doi.org/10.1016/j .jclepro.2023.136598.

Creutzig, F., Acemoglu, D., Bai, X., Edwards, P.N., Hintz, M.J., Kaack, L.H., Kilkis, S., **Kunkel, S.**, Luers et al. (2022): Digitalization and the Anthropocene. Annual Review of Environment and Resources; 47(1). https://doi.org/10.1146/annurev-environ-120920-100056 .

Matthess, M., & **Kunkel, S.** (2022). Supplier sustainability assessment in the age of Industry 4.0–Insights from the electronics industry. Resources, Conservation and Recycling 182, 106274. https://doi.org/10.1016/j .clscn.2022.100038.

Niehoff S., Matthess M., Zwar C., **Kunkel, S.**, Ting G., Ling C. et al. (2022). Sustainability related impacts of digitalisation on cooperation in global value chains: An exploratory study comparing companies in China, Brazil and Germany. Journal of Cleaner Production 134606. https://doi.org/10.1016/j .jclepro.2022.134606.

Schmelze, F., **Kunkel, S.**, Matthess, M., Beier, G. (2022). Digitalisierte Industrie und Nachhaltigkeit zwischen Synergie und Dissonanz. Industrie 4.0 Management, 3/2022. URL: https://industrie-management.de/node/496.

Beier, G., Fritzsche, K., **Kunkel, S.**, Matthess, M., Niehoff, S., Reißig, M., van Zyl-Bulitta, V. (2020). A green digitalized economy? Challenges and opportunities for sustainability. URL: https://publications.iass-potsdam.de/rest/items/item_6000196_1/component/file_6000197/content.

Fritzsche, K., **Kunkel, S.**, Matthess, M. (2020). Digitalized economies in Africa. Structural change in a dynamic environment. IASS Factsheet. URL: https://publications.iass-potsdam.de/rest/items/item_6000438_1/component/file_6000439/content.

Matthess, M., & **Kunkel, S.** (2020). Structural change and digitalization in developing countries: Conceptually linking the two transformations. Technology in society, 63, 101428. https://doi.org/10.1016/j.techsoc.2020.101428.

Appendix C: Conferences

Articles from this dissertation have been presented on various occasions on-site and online (due to the Covid-19 pandemic):

Study 1:

- 29th of August 2019: Presentation at KOSMOS conference, Humboldt-Universität zu Berlin
- 4th of June 2020: Presentation (online) at Nexus conference Dresden

Study 2:

- 10th of June 2021: Presentation (online) in Digitalisation Research and Network Meeting, organised by DigiMeet 2021
- 7th of December 2021: Presentation (online) in conference "Sustainability in Global Value Chains", organised by UNIDO, IfW, Giga, DIE
- 13th of October 2022: Presentation (online) in webinar „Industrie 4.0 und Nachhaltigkeit, Globale Wertschöpfungsketten nachhaltig und digital gestalten'" organised by „Plattform Industrie 4.0"

Study 3:

- 8th of December 2022: Presentation in "Energy Seminar Series", organised by Environmental Change Institute, University of Oxford, Great Britain

Overall thesis:

- 23rd of May 2023: Keynote speech on digital rebound effects at symposium "Sustainability and Digitization: Social Innovation and Rebound Effects", Jönköping International Business School, Sweden

Appendix D: Additional information

Tools and Resources

In the preparation and drafting of this work, I mainly used the following softwares: Microsoft Office, Overleaf (Online Latex Editor), MaxQDA (document analysis software), and R (open source data analysis software). After the preparation and drafting of the original work, I received suggestions from a professional proofreader and used text-correction software in the revision process, in order to improve the orthography, grammar, and style of the written English text. In a final step, I reviewed and edited all suggested changes.

I additionally received help from the following student assistant who worked in the research group "Digitalisation and Sustainability Transformations" at the RIFS Potsdam (former IASS Potsdam): Mandy Hoffmann, Simon Terhorst, Semih Özsoy, Claudia Zwar, Sara Bejtullahu, Frieder Schmelzle, Gereon Fju Mewes, Melissa Dachrodt, Calvin Hanebeck, David Leoncio.

Statement of Contribution and co-author permission statements

Stefanie Kunkel authored the introduction, discussion, and conclusion sections of this dissertation independently. The authorship contributions to each article are stated below the articles. Separate signed co-author permission statements by each co-author are submitted alongside this dissertation.

Appendix E: Langzusammenfassung

Hintergrund

Die Digitalisierung der Industrie, auch „Industrie 4.0“[23], im Sinne einer Vernetzung von Maschinen, Organisationen und Menschen in der Industrie durch digitale Technologien, verändert globale Wertschöpfungsprozesse. Sie hat damit auch Einfluss auf die Umweltauswirkungen des industriellen Sektors (Stock und Seliger 2016), der nicht nur 25 % der globalen CO_2-Emissionen verursacht (IEA 2023), sondern auch zahlreiche weitere Umwelt-Probleme, wie hohe Materialbedarfe und Abfallproduktion, mit sich bringt (Gaussin u. a. 2013). Vor dem Hintergrund der Klimakrise und anderer drängender Umweltprobleme ist eine tiefgreifende, industrielle Transformation erforderlich, durch die der Ressourcenverbrauch und die Emissionen der Industrie gesenkt werden, um die ökologische Kapazität des Planeten nicht weiter zu überschreiten (Sachs u. a. 2019; UNEP 2011). Dies wirft auch die Frage umweltfreundlicherer und fairer Pfade sozio-ökonomischer Entwicklung im Globalen Süden auf (Cranston und Hammond 2010; Sovacool u. a. 2021).

Um sozio-ökonomische und ökologische Ziele in Einklang zu bringen, setzen politische und wirtschaftliche Akteure Hoffnungen auf die Digitalisierung der Industrie, welche eine nachhaltige(re) Industrie-Produktion ermöglichen soll (bitkom 2021; Bradu u. a. 2022; European Commission 2022; European Digital SME Alliance 2020; George, Merrill und Schillebeeckx 2020; GeSI 2020; Mabkhot u. a. 2021; Sachs u. a. 2019; World Economic Forum 2017). Positive Visionen der Industrie 4.0 zur Erreichung von Nachhaltigkeitszielen tauchen weltweit vermehrt in politischen Strategien, wie dem Plan zur „digital and green twin transition“ der EU oder dem „Internet Plus“ Programm Chinas (European Commission 2022; State Council 2015a), sowie in der Kommunikation von wirtschaftlichen Akteuren auf (bitkom 2021; GeSI 2020; Plattform Industrie 4.0 2019; WEF/PwC 2020). Die wissenschaftliche Bewertung der Effekte von Digitalisierung auf ökologische Nachhaltigkeit ist hingegen ambivalent. Positive und negative Gesamteinschätzungen, z.B. in Hinblick auf den Einfluss der Digitalisierung auf Energieverbrauch und Emissionen, stehen sich gegenüber (Freitag u. a. 2021; Wang und Xu 2021; Zhang und Wei 2022).

Herausforderungen bestehender Forschung

Die Unterschiedlichen Erwartungen und Behauptungen verschiedener Akteure, sowie widersprüchliche Befunde der Wissenschaft haben dabei unterschiedliche Gründe. Wirtschaftliche und politische Akteure verfolgen etwa ökonomische Ziele im Zusammenhang mit der Erwartung von Produktivitätssteigerungen und wirtschaftlichem Wachstum durch Digitalisierung. Bestehende wissenschaftliche Studien sind hingegen in Bezug auf die Industrie 4.0 häufig von methodischen Schwächen geprägt (Beier u. a. 2020c; Beltrami u. a. 2021). Durch das relativ junge Konzept der Industrie 4.0, und aufgrund verschiedener Konzepte von ökologischer Nachhaltigkeit und deren Messbarkeit bestehen etwa bisher keine einheitlichen Definitionen und umfangreiche Datensets für die Analyse der Umwelt-Effekte der Industrie 4.0. Zudem sind Untersuchungen aufgrund höherer Datenverfügbarkeit häufig auf Länder des Globalen Nordens bezogen, obwohl die künftigen Umwelteffekte der Industrie 4.0 auch maßgeblich von deren Umsetzung und Auswirkungen im

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[23] Der Begriff „Industrie 4.0“ wird synonym mit dem Ausdruck „Digitalisierung in der Industrie“ verwendet.

Globalen Süden beeinflusst werden (Beier u. a. 2020b; UNCTAD 2019). Darüber hinaus lassen bestehende Studien häufig die systemischen Abhängigkeiten zwischen relevanten politischen und ökonomischen Systemen (Zhang und Wei 2022), Erwartungen und Plänen verschiedener Akteure (Melville 2010), der Technologie-Entwicklung und der Umwelteffekte unberücksichtigt. Daraus resultiert eine lückenhafte Einschätzung der (zu erwartenden) Umwelteffekte der Digitalisierung der Industrie.

Inhalte und Ziele der Dissertation

Vor diesem Hintergrund verfolgt meine kumulative Dissertation[24] das übergeordnete Ziel, angesichts widersprüchlicher Einschätzungen und Erwartungen hinsichtlich der Effekte der Industrie 4.0 die beobachteten Auswirkungen auf ökologische Nachhaltigkeit anhand von drei empirischen Studien zu untersuchen, durch die Synthese der empirischen Ergebnisse Potenziale und Risiken für ökologische Nachhaltigkeit auf verschiedenen Systemebenen abzuleiten und praktische Handlungsempfehlungen für Akteure aus Politik und Industrie vorzuschlagen. Ich stelle drei übergeordnete Forschungsfragen:

1. Was sind die erwarteten und beobachteten Effekte der Digitalisierung in der Industrie auf ökologische Nachhaltigkeit, unter Berücksichtigung der Perspektiven von politischen Entscheidungsträger*innen und Industrievertreter*innen sowie statistischer Daten im globalen Norden und Süden?
2. Welche Chancen und Risiken entstehen durch die Digitalisierung in der Industrie für ökologische Nachhaltigkeit?
3. Welche möglichen Handlungsfelder existieren für die Förderung einer ökologisch nachhaltigeren Industrie durch Politik und Wirtschaft?

Die Gestaltung der Forschungsfragen ist durch vier Annahmen zur Eingrenzung des Forschungsfeldes geprägt, die sich aus den oben beschriebenen Herausforderungen bestehender Forschung und den verfolgten Zielen der Arbeit ergeben (siehe auch Kapitel 1.4 und 1.5). Erstens nutze ich einen interdisziplinären und Multi-Akteurs-Zugang zum Forschungsthema, wobei meine Untersuchungen auf Konzepten aus der Betriebswirtschafts- und Volkswirtschaftslehre, der Politikwissenschaft, der Nachhaltigkeitswissenschaft und der (Technik-)Soziologie fußen. Der interdisziplinäre und Multi-Akteurs Zugang erlaubt es mir, einerseits normative Fragen und Konflikte in der Definition und Deutung verschiedener Konzepte („ökologisch nachhaltige Industrie“, „Digitalisierung in der Industrie“, u.a.) zwischen Akteuren zu diskutieren und andererseits auf verschiedene Datenquellen und Methodiken zuzugreifen, um die geringe Verfügbakeit an Daten zum Themenfeld zu überwinden. Zweitens beschränke ich mich auf die ökologische Dimension von Nachhaltigkeit, um die Breite des Nachhaltigkeitsbegriffs und seine Interpretationen im Kontext der Industrie einzugrenzen. Ich argumentiere jedoch in meinen Artikeln und in der Diskussion stets auch vor dem Hintergrund sozio-ökonomischer Trade-offs, die mit der Nachhaltigkeitstransformation der

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[24] Die Dissertation entstand im Rahmen der Forschung in der Forschungsgruppe „Digitalisierung und Transformation zur Nachhaltigkeit“ am Research Institute for Sustainability (RIFS), Helmholtz Zentrum Potsdam.

Industrie einhergehen. Basierend auf der Diskussion ökologischer und sozio-ökonomischer Zielkonflikte schlage ich Handlungsfelder vor, die meiner Analyse nach Kompromisse in Hinblick auf diese Zielfkonflikte darstellen und von relevanten Akteursgruppen in der Gesellschaft unterstützt werden (könnten). Drittens betrachte ich die Beispiele Chinas (alle Studien) und weiterer Länder des Globalen Südens (erste Studie), um Perspektiven aus dem Globalen Süden einzubringen, welche bisher in der Forschung zu Umwelteffekten der Industrie 4.0 unterrepräsentiert sind. Viertens nehme ich einen soziotechnischen Blickwinkel ein (Beier u. a. 2020c). Ich betrachte somit technische Entwicklungen, Organisationen, individuelles Verhalten und den politischen Rahmen der Digitalisierung in der Industrie als gegenseitig voneinander abhängig.

Forschungsmethoden und Ergebnisse

Meine kumulative Dissertation besteht aus drei empirischen Studien, in denen ich mittels qualitativer Methoden zwei Akteurs-Perspektiven (von Politiker*innen und Industrieunternehmens-Vertreter*innen) untersuche, sowie eine quantitative Analyse zum Zusammenhang von Industrie 4.0 und Energieverbrauch in China durchführe. Ich verwende somit jeweils unterschiedliche, auf die Fragestellungen in den jeweiligen Studien zugeschnittene Methoden.

Konkret untersuchen wir in der ersten Studie (Kapitel 2, gemeinsame Arbeit mit Marcel Matthess) mittels qualitativer Inhaltsanalyse Digital- und Industriestrategien aus sieben verschiedenen Ländern in Afrika und Asien auf politische Erwartungen hinsichtlich der Auswirkungen von Digitalisierung auf Nachhaltigkeit und vergleichen diese mit den erwartbaren Potenzialen für Nachhaltigkeit and verbundenen wissenschaftlichen Analysen der Technologien in den jeweiligen Länderkontexten. Erstens stellen wir fest, dass die Mehrheit der politischen Dokumente, die wir zunächst gescannt hatten (25 von 38), keine Erwartungen hinsichtlich der Auswirkungen von Informations- und Kommunikationstechnologie (IKT) auf die ökologische Nachhaltigkeit der Industrie in Ländern mit niedrigem und mittlerem Einkommen enthielten. Zweitens kategorisieren wir bei den 13 Dokumenten, die derartige Erwartungen enthalten, die Erwartungen dahingehend, ob sie sich auf direkte oder indirekte Umwelt-Effekte[25] beziehen und ob sie als Chancen oder Risiken für die ökologische Nachhaltigkeit wahrgenommen werden. Unsere Analyse ergibt, dass die Dokumente ein breites Spektrum vager Erwartungen zum Ausdruck brachten, die sich eher auf positive indirekte Auswirkungen der IKT-Nutzung, z. B. auf eine verbesserte Energieeffizienz und ein besseres Ressourcenmanagement, und weniger auf negative direkte Auswirkungen der IKT, z. B. auf den Stromverbrauch durch IKT, beziehen. Drittens kategorisieren wir die Erwartungen in vier Teilbereiche, Ressourceneffizienz, nachhaltige Energie, Transparenz und systemische Effekte, und ordnen Beispiele aus den Dokumenten in diesen vier Teilbereichen in den wissenschaftlichen Diskurs hinsichtlich ihrer Potenziale und Risiken ein. Wir argumentieren, dass es für die Digital- und Industriepolitik im Globalen Süden ein Zeitfenster für eine digitale und industrielle Transformation geben kann, bei der die ökologische Nachhaltigkeit im Mittelpunkt steht und beschreiben, wie digitale Technologien spezifisch zur sozial-ökologischen Transformationen beitragen könnten. Der Mehrwehrt der ersten Studie besteht darin, dass durch die Herangehensweise der Politikana-

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[25] Direkte Umwelt-Effekte treten entlang des Lebenszyklus der digitalen Technologie auf, indirekte Umwelt-Effekte entstehen durch den Einsatz digitaler Technologien in anderen Sektoren (wie Industrie oder Landwirtschaft) (Hilty u. a. 2006)

lyse ein Blickwinkel auf die weniger untersuchte Digitalisierung der Industrie im Globalen Süden ermöglicht und die Akteursperspektive der Politik analysiert wird. Diese Perspektive ist vor allem zum Verständnis politischer Prioritäten, Kommunikation und Strategien hinsichtlich der Nachhaltigkeitsauswirkungen von Digitalisierung in der Industrie auf der nationalen und internationalen Ebene wichtig.

In der zweiten Studie (Kapitel 3, gemeinsame Arbeit mit Marcel Matthess, Grischa Beier und Bing Xue) führen wir Interviews mit 18 Industrie-Vertreter*innen der Elektronikindustrie aus Europa, Japan und China zu Maßnahmen der Digitalisierung in Lieferketten und analysieren diese mittels qualitativer Inhaltsanalyse . Wir untersuchen, welche Chancen, Risiken und Hürden für die Zusammenarbeit zum Thema Nachhaltigkeit in den Lieferketten zwischen Käufer*innen und Zuliefer*innen im Kontext der Industrie 4.0 entstehen. Wir stellen zunächst fest, dass eine breite Palette digitaler Technologien derzeit in der Zusammenarbeit in der Lieferkette eingesetzt werden, von E-Mail-basierter Kommunikation bis hin zu automatisiertem Datenaustausch über Online-Plattformen. Wir teilen die eingesetzten digitalen Technologien in unterschiedliche Reifegrade von *niedrig* (digitale Basistechnologien) über *mittel* (z.B. ERP Systeme) bis hin zu *fortgeschritten* (Industrie 4.0-Technologien) ein. Wir stellen jedoch ebenfalls fest, dass der Einsatz dieser Technologien für Nachhaltigkeitszwecke noch wenig ausgepräßt ist, da Interviewpartner*innen nur begrenzt Beispiele aus den eigenen Unternehmen aufzeigen können, wo durch Digitalisierung der Lieferkette bereits Nachhaltigkeitsziele verfolgt oder Nachhaltigkeits-Effekte, wie Ressourceneinsparungen, nachweisbar erzielt wurden. Wir führen das Konzept des "digitalen ökologischen Upgradingsëin, um die Integration der Digitalisierung in den Prozess des "ökologischen Upgradings"[26] in der Lieferkette zu beschreiben. Wir erörtern Chancen, Risiken und Hindernisse von digitalen Technologien sowie Empfehlungen für Hebel zur Gestaltung der (digitalen) Zusammenarbeit für sozio-ökologisch nachhaltiger Lieferketten. Der Mehrwert der zweiten Untersuchung liegt darin, die Akteurs-Perspektiven von Industrievertreter*innen besser zu verstehen, die die Digitalisierung üblicherweise vorwiegend aus einer ökonomischen Motivation vorantreiben, und ökonomisch-sozial-ökologische Zielkonflikte, sowie Win-Win Situationen der Digitalisierung der Lieferkette zu identifizieren.

In der dritten Studie (Kapitel 4, gemeinsame Arbeit mit Peter Neuhäusler, Marcel Matthess und Melissa Dachrodt) führen wir eine statistische Analyse (ökonometrische Panel-Daten-Analyse) durch. Wir untersuchen den Zusammenhang zwischen dem Grad von Industrie 4.0 und Energienutzung sowie Energieintensität in zehn Fertigungssektoren in China im Zeitraum zwischen 2006 und 2019. Der Grad der Industrie 4.0 wurde approximiert durch den Anteil von Industrie 4.0-relevanten Patenten kombiniert mit der Intensität von Industrie-Roboter-Nutzung. Die Ergebnisse deuten darauf hin, dass es insgesamt keinen signifikanten Zusammenhang zwischen dem Grad von Industrie 4.0 und dem Energieverbrauch bzw. der Energieintensität in Fertigungs-Sektoren in China gibt. Es kann eine negative Korrelation von Industrie 4.0 und Energieintensität in hoch digitalisierte Sektoren festgestellt werden, was die Erkenntnis aus früheren Studien unterstützt, dass die Digitalisierung eine energieintensitätssenkende Wirkung in technologieintensiven Sektoren haben kann. Andererseits kann eine positive Korrelation von Industrie 4.0 und Energie-

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[26] Das „ökologische Upgrading“ (engl. „environmental upgrading“) wird als Mittel zur Verbesserung der ökologischen Nachhaltigkeit durch technologischen Transfers in globalen Wertschöpfungsketten, z.B. an weniger technologisch fortgeschrittene Partner*innen, angesehen (Achabou, Dekhili und Hamdoun 2017; Golini u. a. 2018)

verbrauch für Sektoren mit niedrigem Energieverbrauch festgestellt werden, was dadurch erklärt werden könnte, dass die Digitalisierung, z. B. die Automatisierung zuvor hauptsächlich arbeitsintensiver Sektoren, selbst Energie erfordert und außerdem Wachstumseffekte hervorruft. Die Ergebnisse werden vor dem Hintergrund verschiedener Aspekte diskutiert, die in bisherigen Studien häufig unberücksichtigt blieben: (digitale) Rebound-Effekte und internationale Produktionsverlagerung durch Digitalisierung. Abschließend werden in der Studie industrie-politische Optionen erörtert, um den Energieverbrauch der fertigenden Sektoren zu reduzieren und die Implementierung von Industrie 4.0 stärker auf eine nachhaltigere Fertigung auszurichten. Der Mehrwert der dritten Studie besteht darin, eine quantitative Auswertung des Effekts von Industrie 4.0 auf den Energieverbrauch auf der Ebene von Fertigungs-Sektoren in China vorzulegen, und Limitationen statistischer Analysen zum Einfluss von Digitalisierung auf Energieverbrauch, die u.a. durch unterschiedliche Systemgrenzen (Sektor, Land, international) entstehen, am Beispiel Chinas zu diskutieren.

Die Ergebnisse der drei empirischen Studien dienen im Anschluss zur Beantwortung der übergeordneten Forschungsfragen 2 und 3, die ich im Diskussionsteil (Kapitel 6) dieser Dissertation diskutiere. Zum vertieften Verständnis der Ergebnisse nutze ich in der Diskussion das Ordnungsschema der drei Ebenen Makro (nationale und internationale Politik), Meso (Sektoren-/Lieferketten) und Mikro (Unternehmen), sowie von direkten und indirekten Umwelteffekten. Hier liegt mein Fokus insbesondere auf der Einordnung von Potenzialen und Risiken. In der Diskussion gehe ich etwa auf die Wahrscheinlichkeit von und mögliche Maßnahmen gegen Rebound Effekte/n der Digitalisierung auf Mikro-, Meso- und Makro-Ebene, der Verknüpfung von Akteurs-Perspektiven und wissenschaftlichen Erkenntnissen über die Betrachtungs-Ebenen hinweg, z.B. zur Gestaltung von Digitalisierung im Rahmen aktuell diskutierter Lieferkettengesetzgebung, und Aspekte der politischen Ökonomik (Mathai et al., 2021) ein. Letztlich schlage ich Aktionsfelder vor, wie z.B. privatwirtschaftliche und politische Annäherung an ambitioniertere Nachhaltigkeitsverständnisse im Kontext von Digitalisierung in der Industrie gelingen kann, z.B. mittels ko-kreativer Innovationsansätze (Barile u. a. 2020; Grunwald 2022), alternativer ökonomischer Indikatoren (Zhang und Zhu 2022) und Suffizienz-Strategien (Santarius u. a. 2022)

Beitrag der Dissertation

Die Dissertation leistet zwei übergeordnete Beiträge zum wissenschaftlichen und gesellschaftlichen Diskurs. Erstens erweitern meine drei empirischen Studien den begrenzten Forschungsstand an der Schnittstelle zwischen Digitalisierung in der Industrie und nachgewiesener Nachhaltigkeit, insbesondere durch Berücksichtigung ausgewählter Länder im Globalen Süden und des Beispiels Chinas. China ist aufgrund seiner Bedeutung als größterer industrieller Fertiger (30 % der globalen Fertigung (UNIDO 2022)) und als weltweit größter Kohlenstoffdioxid-Emittent ein relevanter Analysefokus. Ein verbessertes Verständnis über die Rolle Chinas für Digitalisierung und Nachhaltigkeit in globalen Lieferketten dient auch dazu, global effektive Maßnahmen zur Kopplung von Digitalisierung und Nachhaltigkeit für Unternehmen und Politik zu identifizieren, indem etwa Handels-Dynamiken und internationale Verlagerung von Umwelt-Effekten berücksichtigt werden (zur Auswahl Chinas als Analysefokus siehe auch Kapitel 1.5).

Zweitens ermöglicht die Erforschung des Themas durch Daten und Methoden aus unterschiedlichen disziplinären Kontexten, aus Akteursperspektiven und unter Einnahme eines soziotechnischen Standpunkts, eine Analyse von (Pfad-)Abhängigkeiten und Unsicherheiten im soziotechnischen System über verschiedene Analyse-Level hinweg, die in bisherigen Studien häufig nicht ausreichend berücksichtigt werden (Renn, Beier und Schweizer 2021; Trevisan u. a. 2023; Zhang und Wei 2022). Die wissenschaftlich erfassten Potenziale und Effekte werden anhand des aktuellen Stands der Literatur auf den drei Analyseebenen in der Diskussion kontextualisiert, Wirkungszusammenhänge und Abhängigkeiten auch zwischen den Ebenen diskutiert und damit eine umfassendere Entscheidungsbasis für Maßnahmen zur Steigerung der Nachhaltigkeit der (digitalisierten) Industrie bereitgestellt. Die Dissertation soll so letztlich einen Baustein zur Schaffung von breiten gesellschaftliche Initiativen für eine werte-geleitete Gestaltung der Digitalisierung der Industrie bilden (Renn, Beier und Schweizer 2021).

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