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SPECIAL ISSUE:

SUSTAINABLE DIGITALIZATION – FOSTERING THE TWIN TRANSFORMATION IN A TRANSDISCIPLINARY WAY

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How sustainable is the digital world?

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The world we live in is characterized by rapid change. Even people who lived around the middle of the 20th century would hardly be able to find their way around today. Internet, computers, mobility, communication, robots are just some of the modern side effects of the manifold transformations in technology and society. This is especially true for the topic of digitalization, which is the main focus of this *GAIA* issue.

Digitalization emerged in three stages: automation, algorithmization and autonomization. With the new Chat GPT service, progress in these stages has reached the wider society.[1] But with all this development, the question remains: how sustainable is this development? What are the impacts on the ecological, economic and social dimensions of sustainability?[2] On the one hand, there are high gains in convenience and efficiency, better possibilities for recording and controlling material and energy flows in models of the circular economy, and more opportunities for individuals and groups to develop their own agendas. On the other hand, digital systems require vast amounts of energy, encourage increasing consumption, and may also lead to restrictions on personal freedoms and loss of identity. Cyber risks threaten to cripple entire functions of a society. Abuse of power and possible loss of autonomy due to progressive algorithmization are also among the systemic risks. At the same time, digitized processes offer the opportunity to both strengthen democratic structures (transparency, simplified access to political participation, e-democracy), but also the risk of significantly weakening them (bots, latent manipulation, echo bubbles).

The tension between digitalization and sustainable development is exemplified by smart industrial production, known in Germany as "Industry 4.0". Innovations in the direction of Industry 4.0 allow less material input, less emissions and waste and more efficient use of resources, but can also restrict individual autonomy, reduce one's agency and become a threat to one's own identity. Furthermore, resource and energy consumption, the opposite of what is envisioned, can increase as a result of higher production and operation of the digital devices. A comprehensive risk-benefit assessment is required.

Another focus of digital transformation is the application in private settings. Keywords such as "smart home" or "smart cities" describe a new reality of life in which intelligent services ranging from energy, security and health monitoring to entertainment and communication are largely performed autonomously by intelligent control units.[3] To what extent this smart living world supports or hinders sustainable structures in terms of ecology, economy and social functions is still an open question.

The articles in this issue shed light on these questions and provide initial answers to the challenges of digitalization. It becomes clear that digitalization will not reduce the ambivalence of technological change. What matters now is to improve and support the positive opportunities and minimize the associated risks through wise and foreseeable regulation. To do this, we need further committed research and courageous policies.

Ortwin Renn

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COVER PICTURE

This visualization features a common vision of a city of the future: a skyscraper megacity with the icons for Wi-Fi, Internet, public transport, etc., superimposed to symbolize information and networked technologies and digital data flows. Since the millennium, the idea of smart cities has been thriving, promising to solve urban development problems through digitalization, and thus make cities more efficient and sustainable. However, whether smart city strategies have a positive or negative impact on sustainability is highly debated. We need to ask ourselves why narratives of digitalization and sustainability are so often connected with smart megacities and skyscrapers. Is this a future we really wish for? We should keep in mind that with the projection of our ideas and hopes of the future we both open and close spaces of opportunities for a sustainable transformation of our societies.

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SPECIAL ISSUE: SUSTAINABLE DIGITALIZATION – FOSTERING THE TWIN TRANSFORMATION IN A TRANSDISCIPLINARY WAY

Modern societies are shaped by digitalization and challenged by sustainability transformations. The question of how digitalization can support a green transformation has become more and more common in public discourse, scientific research and political agendas. At the same time, direct environmental harm caused by digitalization, as well as its contribution to the promotion of unsustainable lifestyles, is critically discussed. Moreover, digitalization not only affects environmental sustainability. Issues of data governance and innovative forms of participation are controversial topics in digitalization and social sustainability. In this special issue, theoretical and empirical papers are presented that aim to address digitalization and sustainability in an integrated way. The collection connects scientific and political discourses and provides both analysis and recommendations for action.

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Robert Bosch Stiftung

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12 QUESTIONS TO ECKHARD STÖRMER

1. From your point of view, what are today's most pressing environmental problems?[1]

We experienced another hottest summer, dramatic wildfires, and other extreme events. 1 in a 100 or 1000 year events turn to become the regular normal. We witness a culmination of climate change, biodiversity loss, increasing consumption of land, and man-made emissions like nitrate pollution of water bodies and microplastics in the seas, etc. They work in a reinforcing vicious cycle. It seems like earth reached already some tipping points that can lead to a systemic collapse, if humanity does not take U-turn now.

2. When looking at potential improvements in our environment, what gives you hope?

I see three positive signs: societal awareness is high, pro-climate youth protests are influential, and the pandemic has shown that adaptation of people's behaviour at least under specific conditions is possible.

Technological innovation makes green and clean technologies competitive. Digitalisation can enable shift in production and consumption patterns, like circular and sharing economy, servitisation and virtualisation of value propositions.

Dramatic crises make us rethink one-sided supply dependencies that are based on cheap fossil fuel for production and logistics. Reinforcing domestic renewable energy production, repair, sharing and recycling increase Europe's autonomy while contributing to the sustainability transition.

3. Is there a particular environmental policy reform you admire the most?

The *European Green Deal* sets ambitious climate policy targets and is quite encompassing; it includes a broad spectrum of policy areas to contribute from agriculture to transport, financial affairs and international trade, just to name few. Achieving policy coherence across various policies with diverging objectives is a huge challenge, as well as materialising the programme in real life in all areas as soon as possible.

4. Which trend in environmental policy and politics do you consider an aberration?

Trust in the green growth narrative can lead us in a dead-end. The belief that greenhouse gas emissions and resource use can be decoupled from economic growth to the extent needed is not justified. To achieve net-zero carbon targets requires radical transformation of our production and consumption system as well as the social system to achieve a just transition. As Antonio Guterres said recently: "2023 is a year of reckoning. […] We need disruption to end the destruction."

5. Why strategic foresight for sustainability?

Foresight provides a systemic understanding of drivers and change trajectories that push or hinder sustainability. It combines insights from several research domains, connects the dots through coherent logic and takes assumptions about long-term futures. It enables us to think ahead, speculate and immerse into possible and plausive futures through strong narratives. This allows to be prepared and provide strategic plans to actively shape the world and to direct it to the one we want to live in.

6. What has your experience been when it comes to transferring scientific insights into practice?

It is important to take a transdisciplinary approach to solve real-world problems. You need a proper understanding of the problems now and in the future, your objectives, and co-create different solutions that fit the specific context. It requires involvement of the stakeholders in co-creation, learning and assessment of solutions. Legitimate decision makers need to accept the proposal as outcome of process. This requires lobbying for priorities and finding the right window of opportunity in which an adequate solution survives the political negotiation process.

7. What field of research in the environmental sciences do you find most exciting?

The sustainability transition research attracts me, as it shows ways and approaches to change dominating systems to get to more sustainable ones. It combines environmental, social, economic and technological sciences. By highlighting power relationships of actors and path dependencies, it provides an understanding of levers for a transformation.

8. Can you name any person or event that has had a particular influence on your commitment to environmental issues?

When I was a kid, the impressive pictures and news about the "Waldsterben" (forest dieback) strongly influenced my thinking: we cannot take functioning ecosystem for granted, we are destroying our planet through our way of production, and environmental policy is limited, as it has to balance its ambitions and instruments with other policy areas.

1 The views expressed are purely those of the author and may not in any circumstances be regarded as stating an official position of the European Commission or other previous employers.

9. What knowledge about the environment would you like to pass on to young people?

Understand the big picture of our action and the environmental (and social) impacts of our activities as compass for responsible decisions. Just think of the thousands of litres of water footprint when buying a shirt. Your individual action counts, you have a voice. Get active to convince others locally and make your voice heard by engaging in movements like *Fridays for Future*.

10. As a person concerned with environmental issues and foresight, what contradictions do you face in everyday life?

I try to live my life responsibly. But in daily routines, compromises are sometimes necessary, sometimes allowed. And, obviously, I am not a superhero. Experiment and try again every day, but not chasten yourself.

11. What are you reading at the moment?

Walkaway, a speculative fiction novel from Cory Doctorow. It illustrates the living of a subculture that lives in a community based on sharing, everything as commons, open innovation, digitally enabled creation of the necessities. It is a thought provoking story about the dynamics and impacts in and of a different societal model.

12. Apart from the ones we've raised here, what is the most important question of our day?

How can we achieve peace?

Eckhard Störmer,
Futurist at Future Impacts Consulting, Cologne, DE.
Areas of expertise: strategic foresight for private and public sector and governments, technology foresight, innovation management, speculative design, and policy evaluation.

Born 1970 in Munich, DE. Studies in social and economic geography. 2001 doctorate in innovation management at Ludwig-Maximilians-Universität München, DE. He worked 2001 to 2004 on climate change impacts and preparedness to flood events at the Bavarian Water Management Agency, Munich, DE; 2005 on evaluation of sustainability at Vienna University of Economics and Business, Vienna, AT; 2006 to 2011 in water infrastructure and governance related transdisciplinary research projects at Eawag, Swiss Federal Institute of Aquatic Science and Technology, Dübendorf, CH; 2011 to 2017 at Z_punkt The Foresight Consultancy, Cologne, DE, with megatrends and scenario based approaches for strategy development and innovation in various sectors in Europe and beyond; 2017 to 2023 on approaches to futureproof policymaking and on future studies ranging from future of government, green jobs, open strategic autonomy to green and digital transitons at the EU Policy Lab and the Competence Centre on Foresight of the European Commission's Joint Research Centre, Brussels, BE; since 2023 at Future Impacts Consulting, Cologne, DE.

Selected publications: Local strategic planning processes and sustainability transitions in infrastructure sectors (*Environmental Policy and Governance* 2010; with B. Truffer et al.) | From foresight to impact? The *2030 Future of Work* scenarios (*Technological Forecasting and Social Change* 2017; with M. Rhisiart, C. Daheim) | Chapter 12: Foresight – Using science and evidence to anticipate and shape the future (*Science for policy handbook* 2020; with others) | *The future of jobs is green* (Luxembourg 2021; with T. Asikainen et al.) | *Towards a green and digital future* (Luxembourg 2022; with S. Muench et al.)

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ECKHARD STÖRMER

Good politics needs scientific support. Politicians require support to anticipate emerging issues that need to be addressed; to develop policies based on evidence about implications and unanticipated side-effects; to face new challenges requiring the innovation of policy tools; and in the particular case of the European Union, to share knowledge and know-how amongst country governments and European bodies (in Brussels and beyond), but also with the diverse scientific, civil society and business communities throughout its multicultural territory. This is the quest of the Joint Research Centre (JRC), which serves as a think tank to the European Commission and the EU Member States.

Eckhard Störmer has devoted much of his career as a researcher to the JRC and hence, to advance forward looking scientific evidence in EU policymaking. Trained as a social and economic geographer, and with specific professional skills as strategic futurist, Eckhard has developed and applied strategic foresight approaches for policymaking, better regulation and policy priority setting in greatly varying topic areas. Among others, he has worked and published on issues such as the future of work, the energy transition, new forms of government, and the digital transformation. Most notably, he co-authored a number of JCR studies on which *Strategic Foresight Reports* of the European Commission build upon; they help to embed collective intelligence on anticipated future developments into EU policymaking.

His skepticism poses the question: whom and what goals should should technological advancements be serving?

In 2021 and 2022, Eckhard was part of a team of scientists who commissioned a dialogue about the intersection between the green and the digital transitions. Eckhard brought together scientists, policymakers, representatives from civil society and industry, to identify and categorize technology pathways that can enable the green transition into 2050. He investigated current and future digital technologies, and assessed areas of interaction between green and digital transitions to determine where they reinforce or hamper each other. Together with colleagues from the JRC, and a group of external experts, Eckhard eventually synthesized the outcome of a series of science-policy workshops on various sectors (e.g., agriculture, energy), specific issue-related briefing papers and interviews with JRC's own research into the publication of the 2022 *Foresight Report Towards a Green and Digital Future*. Given the limited number of comprehensive publications available on this issue, the report provides yet another milestone for a successful "twinning" of the Union's current two overarching policy goals – the *Green Deal* agenda and the *Fit for the Digital Age* agenda.

As one of the few experts on the topic-nexus of digitalization and sustainability with day-to-day insights into EU policymaking, we have asked Eckhard to share his views on the *12 questions*. And, as you will read, his skepticism regarding the scientific evidence of a green growth strategy poses the important question: whom and what goals should technological advancements eventually be serving?

Prof. Dr. Tilman Santarius, Technische Universität Berlin, Einstein Centre Digital Future, Berlin, DE

Sustainable digitalization – fostering the twin transformation in a transdisciplinary way

Can digitalization be designed in such a way that it does not harm the environment or promote unsustainable lifestyles? Can it even promote a green transformation? The authors of this GAIA special issue discuss how stakeholder engagement and transdisciplinary approaches can help address digitalization and sustainability in an integrated way. The special issue deepens insights into the state of knowledge on sustainable digitalization in both scientific and political discourses.

Matthias Barth, Maike Gossen, Daniel J. Lang, Tilman Santarius

Sustainable digitalization – fostering the twin transformation in a transdisciplinary way | *GAIA* 32/S1 (2023): 6–9
Keywords: digitalization, environmental sustainability, transdisciplinarity, transformation

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In recent years, the link between digitalization and sustainability has become an increasingly relevant topic, both in public debate and in scientific research. It has also risen up the political agenda, at least in some countries. As of February 2022, in the European Union the two overarching narratives were sustainability and digitalization, expressed in the *Green Deal* and *Fit for the Digital Age* legislative packages respectively. And while for many years the connections between the two narratives have only been discussed in niches, the debate is now gaining momentum (Kiron and Unruh 2018). The number of public and policy events on this nexus has also increased, including an international symposium hosted by Leuphana University of Lüneburg, the Einstein Centre Digital Future and TU Berlin, and funded by the Robert Bosch Stiftung, in May 2021 entitled *European approaches towards a Sustainable Digitalization*[1]. In this context, the term “twin transition” is increasingly used by high-level policymakers, including the commissioners and their president. And in 2021, two comprehensive reports were published that systematically explore a policy agenda for sustainable digitalization (D4S 2022, Muench et al. 2022).

While politics and business often unilaterally emphasize the potential of digitalization to increase efficiency and achieve a win-win situation for ecology and economy, the other side of the coin is increasingly coming into focus, namely the challenges posed by digitalization’s disruptive character, such as its increasing contribution to power asymmetries and inequalities, its resource consumption, and its rebound effects (Del Río Castro et al. 2021). The more widely digitalization is understood as a process of social change characterized by “the restructuring of domains of social life around and with digital communication and media infrastructures” (Brennen and Kreiss 2016), the clearer the interdependencies between digitalization and the urgently needed sustainability transformation become.

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1 *www.tu.berlin/en/transformation/events/past-events/symposium-european-approaches-towards-a-sustainable-digitalization-mai-2021*

Indeed, digitalization impacts the goals and strategies of the sustainability agenda on many levels, and vice versa. While research on the topic of "information and communications technology (ICT) for sustainability" is progressing, many questions on this complex of topics have not yet been sufficiently explored. In particular, transdisciplinary approaches to sustainability strategies at various governance levels – from the EU as a whole, to cities and municipalities, to the individual consumer – are still in their infancy. Given the potentials and risks of digitalization as a complex and dynamic process of economic, social, and cultural change, there is a clear need for sustainability research, and also for sustainability strategies and policies which identify the conditions that put digitalization at the service of sustainable development.

This special issue deepens insights into the state of knowledge and possibilities of knowledge transfer, both in scientific and political discourses. It discusses how stakeholder engagement and transdisciplinary approaches can help address digitalization and sustainability in an integrated way. It also discusses challenges and success factors in how certain digital innovations, for example, artificial intelligence in urban planning processes, can contribute to a green transformation.

The journal edition includes six research articles, two forum articles as well as a short interview with 12 questions providing insights on environmental policy making. We are grateful that ***Eckhard Störmer,*** a distinguished researcher from the Joint Research Centre of the European Commission who recently published a report on the interface of the green and digital transformation, committed to respond to our questions. In the interview, he sketches out his personal views on urgent environmental challenges and the understanding of the global environment in the light of fast moving technological progress.

12 Questions to …
pp. 4–5

The six research articles contribute to the overarching questions of this special issue in at least three different ways – 1. by providing an overview of how the discourse on sustainability and digitalization is evolving, 2. by highlighting several topics of high relevance in sustainability science where digitalization is having a significant impact, and 3. by illustrating these impacts through concrete case studies. The six articles fit together seamlessly: the first two provide an overview of "hot topics" as well as shortcomings in current discourses; the following four contribute to the topics.

Discourses surrounding sustainability and digitalization in Europe on Twitter over time
pp. 10–20

Opening this special issue, ***Mario Angst and Nadine Strauß*** reconstruct the evolving discourse on sustainability and digitalization by analyzing a corpus of relevant tweets from the last decade. Based on a qualitative analysis of these tweets, they identify climate change as a central theme, and were able to capture the discourse around the lifecycle impacts of ICT and the increasing importance of the smart city. They also point out a significant blind spot: the structural impact of digitalization on sustainability is, by and large, overlooked in the discussion.

Digitalization and sustainability: A systematic literature analysis of ICT for Sustainability research
pp. 21–32

With similar intent, ***Tilman Santarius and Josephin Wagner*** conducted a systematic review of publications from the *ICT for Sustainability (ICT4S)* research community. The authors raise the question of what kind of sustainability implications of ICT are addressed in this research corpus and offer insights into the discourse taking place within an expert community that can help draw conclusions for funding and science policy. Their findings show that the current *ICT4S* discourse focuses heavily on how digitalization enables (energy) efficiency and how to reduce the lifecycle impacts of ICT devices and applications. However, there are few studies that address the potential of digitalization to promote sufficiency- and consistency-oriented practices, or how digital sustainability transformations can be promoted at the structural level, for example, to achieve a circular economy or a post-growth economy. In their conclusions, the authors draw parallels to these foci in current policy debates within the European Union and suggest how science and funding policies could be further developed to address existing gaps.

>

The next two articles provide contributions that address the discursive deficits identified by Tilman Santarius and Josephin Wagner, namely how ICTs can be used to structurally impact sustainability transformation and policies for a circular economy. ***Matthias Gotsch and his co-authors*** analyze the role of environmental data science applications and shed light on their potential to support the transition to a green economy. Their study not only highlights numerous examples of green economy applications, but can also be used to formulate policy recommendations to better integrate digital technologies into green economy policies. Finally, the authors propose six measures that can help overcome the identified barriers to greater use of data science for green transformation. These range from aspects of data availability and quality to concrete ways to address regulatory hurdles.

The contribution of data science applications to a green economy
pp. 33–39

Dominik Piétron and his co-authors argue that strategic governance of product data is key to designing circular ecosystems with low carbon emissions and minimal consumption of natural resources. Exploring the technical and policy framework required for data-based policy tools, the authors analyze five empirical cases along the product life cycle. Their results show how strategic governance of product-related data can link material and product flows and shape new collaborative circular ecosystems. Applying this data governance perspective to the EU's Digital Product Passport proposal, they believe that the unclear technical specifications for data collection and data standards, as well as the lack of comprehensive material tracking, could create high coordination costs and thus hinder circular ecosystems. Therefore, they propose the creation of publicly coordinated Product Data Platforms that complement the Digital Product Passport by making data more accessible.

Digital circular ecosystems: A data governance approach
pp. 40–46

The next two research articles follow up on the first by Mario Angst and Nadine Strauß by providing contributions to the "hot topics" identified in their Twitter analysis: urban planning and the concept of smart cities for sustainability. ***Florian Koch and his co-authors*** connect the concept of the smart city to sustainability research. They critically reflect on the potential of data from smart city approaches and raise the question of what opportunities new data offer for urban *Sustainable Development Goals* monitoring systems. Using the example of the Berlin district of Treptow-Köpenick, they highlight the potential but also the many pitfalls of implementation, such as technical barriers, difficulties in assessing data quality, and lack of time resources for data maintenance. In conclusion, they argue that the monitoring of smart cities should be understood as both a social and a technological process.

Monitoring the* Sustainable Development Goals *in cities: Potentials and pitfalls of using smart city data
pp. 47–53

Using augmented reality in urban planning processes. Sustainable urban transitions through innovative participation
pp. 54–63

Frank Othengrafen and his co-authors explore how augmented reality can help to both increase motivation for participation and present planning concepts more realistically through various forms of visualization. Using two case studies on sustainable urban development in Vienna and Lucerne, they show how the use of augmented reality not only increases the motivation of the population to participate in planning processes, but also enhances the quality of participation processes and can thus trigger the sustainable transformation of cities.

More sustainable artificial intelligence systems through stakeholder involvement?
pp. 64–70

In addition to the six research articles, this special issue includes two articles in the *Forum* section. In the first article, ***Stefanie Kunkel and her co-authors*** look at the impact of the use of artificial intelligence systems (AI) on the environment. They raise the question of whether and how stakeholder engagement, as a key characteristic of transdisciplinary research, can help us better understand and manage the environmental impacts of AI. In their article, they analyze sustainability frameworks for software and AI, asking to what extent these frameworks consider both the direct and indirect environmental impacts of software and AI, and whether and how stakeholders are involved to identify these impacts. The authors propose ways in which greater stakeholder involvement can benefit the development of sustainable AI.

In the second article of the *Forum* section, ***Maike Gossen and Otmar Lell*** question the prevailing understanding of the interplay between digitalization, sustainability, and consumption. They base their contribution on the diagnosis that the positive trends of digitalization for sustainability are outweighed by the unsustainable consumption patterns of digital business models. The authors discuss how it is possible and necessary to shape digitalization in a way that promotes sustainable consumption. To do so, they illustrate examples of current policy approaches shaping the impacts of digitalization on sustainable consumption, and propose approaches for a systemic policy framework to promote sustainable consumption in digital environments. By introducing a "positive accountability" approach, they offer an alternative to current approaches of "isolated" regulation and suggest an integrated regulatory approach that can lead to a comprehensive assessment of digital business models.

Sustainable consumption in the digital age. A plea for a systemic policy approach to turn risks into opportunities
pp. 71–76

We hope that the articles in this special issue will help advance the discourse on linking digital and sustainability transformation, and that some of the concrete suggestions for decision- and policy-making will resonate beyond the academic community. The articles highlight the complexity of the issue and the particular challenge of acting quickly in the face of the current sustainability crisis, while keeping in mind the risk of unintended side effects. They also show that focusing on shallow leverage points (see Abson et al. 2017), such as increasing the efficiency of technologies and processes, is not enough to truly address these crises and realize the full potential of digitalization. Instead, deeper leverage points, such as system paradigms and structures, must also be considered if current socio-technical-political and ecological systems are to be transformed both digitally and sustainably. Since purely descriptive-analytical research alone – as important as it is – is not enough to promote truly transformative change, we would like to thank all the authors of this special issue for not only providing thorough analyzes, but also making concrete recommendations for action.

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Discourses surrounding sustainability and digitalization in Europe on Twitter over time

Digitalization and sustainability transformations are contested change processes, accompanied by wide public discourse. But what concerns the public? Our analysis of the social media discourse on Twitter in the last decade reveals key discursive hubs such as smart cities and climate change, as well as blind spots such as sufficiency strategies. It also points to differences between societal and academic discourse, and where increased engagement of researchers and sustainability professionals would be needed to move forward.

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Discourses surrounding sustainability and digitalization in Europe on Twitter over time
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Abstract
This study analyzes the discourses surrounding the interrelation between digitalization and sustainability in Europe on Twitter between 2010 and 2021. We identify 34,802 tweets related to the interrelation between digitalization and sustainability among 634,017 tweets discussing sustainability issues with explicit mentions of Europe. Based on a qualitative analysis of tweets, we identify the main domains discussed (and not discussed). We then sketch the development of the identified domains, as well as their relationship to each other over time, based on a quantitative analysis of their (co-)occurrences. We find that smart city and mobility were two of the most dominant and interrelated domains, particularly in the middle of the decade. In parallel, the domain of climate change has gained ever more attention since 2017 and has emerged as a discursive hub. We further develop hypotheses for how external factors and events (especially EU-level programs) likely led to increases in attention to some domains. Finally, we find that the Twitter discourse across domains mirrors common blind spots regarding sustainable digitalization discourses in its uncritical stance toward economic growth and its overreliance on efficiency in comparison to sufficiency concerns.

Keywords
digitalization, discourse, social media, sustainability

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Concerning their discursive power, sustainability and digitalization have become two of the most dominant "megatrends" of our time (Lichtenthaler 2021, p. 64). Particularly since the COVID-19 crisis, public attention to the interrelation between sustainability transformations and digitalization has further intensified, following governments (e.g., *European Green Deal*), intergovernmental associations (e.g., United Nation *Sustainable Development Goals*), and companies promoting sustainability and digitalization as joint strategic goals (cf. Del Río Castro et al. 2021, Lichtenthaler 2021).

However, research in the past has focused primarily on the theoretical and conceptual relationship between digitalization and sustainability transformations (e.g., Lichtenthaler 2021, Seele and Lock 2017). Yet, both refer to socio-technical processes that are driven and accompanied by societal discourses. This is especially relevant to sustainability transformations, which are inherently negotiated in reference to the goal of sustainability as a normative concept. Beyond the normative and empirical discussion of how the potential for sustainability transformations co-evolves with digitalization, it becomes equally relevant to study the interrelation between the discourses of sustainability and digitalization in the public domain over time (e.g., Andersen et al. 2021, Galaz et al. 2021). Analyzing and understanding the public discourses concerning these two processes are of crucial importance to determine the feasibility and direction of transformations and to identify future pathways, main drivers, and dominating or (under)represented discourses.

Societal discourses take place in different forms and in different fora and environments. We take one of various possible approaches and analyze the social media discourse surrounding digitalization and sustainability on the platform Twitter, a widely researched social medium that has been identified to reflect public discourse on a variety of topics (e.g., politics: Ott 2017). In the context of this special issue, we also conducted our analysis with a specific focus on the European discourse: how has the social media discourse on the interplay between sustainability and digitalization in the European context been structured on Twitter between 2010 and 2021, and what were likely causes of changes to the structure of the discourse during this time?

Conceptual framework

Sustainability transformations and digitalization: Two interrelated processes

We view sustainability as a normative concept of intra- and intergenerational justice and human flourishing within planetary boundaries (Steffen et al. 2015, Raworth 2017). As such, sustainability transformations are socio-technical change processes oriented toward sustainability (Schneidewind 2018), and they occur next to and interact with other socio-technical change processes, one of which is digitalization. Following Bockshecker et al. (2018, p. 8), we define digitalization as “the state of an organization or a society referring to its current digital development and usage of ICT innovations. Digitalization takes into account social as well as technical elements”.

Information and communication technologies (ICT) has become a constant in the new “digital age” (Schmidt and Cohen 2013). However, while digitalization offers new opportunities to save resources, engage citizens, and limit carbon emissions, scholars have also argued that the way new technologies are employed can be counter-productive to achieving sustainability goals. Some even advocate for a general “digital reset” to re-calibrate the relationship between digitalization and sustainability, arguing that fundamental developments in how digitalization plays out in societies in its orientation toward economic growth, its single-minded focus on efficiency, and its lack of participation must be reset to achieve societal transformation toward sustainability (D4S 2022). Regarding resource use, for example, digital infrastructures and technological devices (e.g., smartphones, batteries) have been shown to require large amounts of energy and natural resources, and their resource efficiency potentials are often dwarfed by rebound effects (Hilty and Aebischer 2015). Digitalization is also reshaping resource and power distributions within societies, with ambiguous results in terms of inter- and intragenerational justice, which is a core tenet of sustainability as a normative goal. Despite a plethora of research concerning sustainability transformations and digitalization separately, scholars have also pointed out that research investigating both societal change processes jointly is still limited (Del Río Castro et al. 2021, Lichtenthaler 2021) and often lacks interdisciplinary perspectives and approaches.

Sustainability and digitalization discourses

Sustainability transformations and digitalization are not only two interrelated socio-technical change processes, but they are also accompanied and driven by societal discourses. This is especially relevant to sustainability transformations, which are broadly discussed in reference to sustainability as a normative concept, but also interpreted, contested, and translated constantly by a variety of actors. This is also true for digitalization – which is not an entirely self-referential technical process – without reference to the normative stances of the actors involved in shaping it. Indeed, the course that digitalization follows in society is largely dependent on how it is framed and perceived in public discourses, which is additionally affected by institutions and power structures (Marenco and Seidl 2021).

However, few empirical studies have investigated the interplay between digitalization and sustainability in the public discourse, and this is especially true for mediated societal discourses. Following Brenner and Hartl (2021, p. 4), the news media are central to “creating and reproducing discourses about how digitalization and sustainability interact”. Based on the agenda-setting theory (McCombs and Shaw 1972), it is argued that the news media, including social media, have the power to influence what concerns the public. In effect, much research in the field of communication studies has found that the issues being discussed prominently in the news media transfer to the minds of the public, thus ranking highly on the public agenda (e.g., Kiousis and McCombs 2004). In this study, we equally assert (but do not aim to prove empirically) that in combination with the relative attention given to various aspects of the discourse on digitalization and sustainability, their presentation on media platforms (e.g., Twitter) ultimately contributes to the conditions under which processes play out in societies, particularly in terms of regulation or policymaking (cf. Soroka 2002).

While scholars have extensively studied the coverage of climate change (Hase et al. 2021) and, to a smaller degree, the representation of new, digitalization-adjacent technologies (e.g., nanotechnology: Metag and Marcinkowski 2013, digitalization in agriculture: Mohr and Höhler 2021) in the news media, the interrelation between the two discourses of digitalization and sustainability has received little scholarly attention thus far. Lenz (2021) offers the first qualitative account of three common narratives being used in the public discourse to describe the connection between sustainability and digitalization. On a general level, they distinguish digital technologies as problem solvers, digital tools as opportunities for participation and inclusion, and technological innovations as solutions to ecological disasters. In a similar vein, Brenner and Hartl (2021) qualitatively analyzed news media coverage of sustainability and digitalization in Austrian news from 1990 until 2019 and identified four frames, presenting the relationship between the two processes as a stand-alone challenge (frame 1), a result of the impact of digitalization on sustainability (frame 2), not leading to a sustainable solution (frame 3), and asserting digitalization as a positive catalyst for sustainability (frame 4).

These first analyses offer a qualitative overview of the narratives and frames being used in the discourse surrounding digitalization and sustainability, mainly based on print news. However, a more encompassing assay of how the discourse has evolved on a broader scale, on more timely platforms for public discourses (e.g., social media), and over time is currently lacking. In fact, previous research has suggested expanding the analysis of the discourse on digitalization and sustainability from the news media to social media (Brenner and Hartl 2021). Thus, we contribute to filling this gap by analyzing social media discourse, specifically on the microblogging service Twitter, with a specific focus on Europe.

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Methods

We empirically analyze the occurrence, relative weight, and, to some extent, framing and likely drivers of different aspects of the English-language discourse on the interplay between sustainability and digitalization in Europe over time on the social media platform Twitter between 2010 and 2021. To answer our research questions concerning the structure of the Twitter discourse over time and the external factors likely to explain them, we focus on three key aspects. First, we inductively identify distinct discourse domains. Second, we then analyze the occurrence and co-occurrence of these discourse domains over time and explore likely drivers of trends and patterns. Finally, we investigate the presence or absence of two key transversal discourse topics, which are core components of critical academic and policy discussions surrounding digitalization and sustainability (D4S 2022): framing of sustainability and digitalization regarding economic growth and the reliance on a narrative of resource use efficiency gains regarding digitalization, as well as considerations of sufficiency strategies.[1]

At the time of our analysis (spring 2022), Twitter was a privately owned social media platform, which at its core allowed users to formulate short statements restricted to 280 characters (so-called tweets, a form of microblogging), optionally accompanied by images, videos, or web links. Authors of tweets were able to share these with other platform users. In addition, users could interact in various ways with tweets, including resharing and liking them. While widely used, Twitter data are by no means a representative or unbiased source for analyzing societal discourse. There are clear limitations fundamentally linked to the fact that data are gathered on a platform not designed for research purposes and set up by a private company. In our case, an analysis of tweets is likely skewed toward aspects of the discourse specifically relevant to elite actors. This is because professional entities or representations (Sloan 2017) and higher socioeconomic classes (Yates and Lockley 2018) have been found to be likely over-represented among Twitter users, including academics, journalists, or politicians.

Analysis pipeline

Our analysis proceeds in three steps. First, we obtain a dataset of tweets relating to the overall discourse on sustainability and digitalization between 2010[2] and 2021 in Europe by querying the Twitter application programming interface (API) with a set of keywords and then training a binary text classifier on the data obtained to arrive at a subset of relevant tweets. Second, we inductively identify a set of domains prevalent in the overall Twitter discourse and assign one or more discourse domains to tweets using pattern matches. Third, we proceed to classify tweets regarding the occurrence of transversal (cross-domain) discourse dimensions, which are (stances toward) economic growth and mentions of efficiency and sufficiency. To do so technically, we build on recent work using zero-shot learning approaches (Gambini et al. 2022).

Step 1 a: Querying the Twitter API

We query the Twitter Academic API (full archive search) with two queries to gather two datasets. First, we gather a starting set of English-language tweets using a relatively narrow search query based on terms used in Andersen (2021) – with a European focus added – and adapted to the requirements of the Twitter API endpoint (figure 1). This yields the dataset *sus_digi_eu*, comprising 15,592 unique tweets.

Query 1:
(digital OR digitalization OR digitalisation OR ict)
AND (sustainable OR sustainability OR SDG)
AND (europe OR european OR eu))
English language, no retweets
between 2010 and 2021

FIGURE 1: Twitter API query 1.

Second, we query the Twitter API with a second query (figure 2) designed to gather a much broader dataset of tweets relating to sustainability in Europe. This resulted in the dataset *sus_eu*, comprising 634,017 unique tweets, which is a superset of *sus_digi_eu*.

Query 2:
(sustainable OR sustainability OR SDG)
AND (europe OR european OR eu)
English language, no retweets
between 2010 and 2021

FIGURE 2: Twitter API query 2.

Step 1 b: Classification of discourse-related tweets

Even a brief inspection of the *sus_eu* dataset resulting from the keyword-based query to the Twitter API reveals it contains many tweets unrelated to the discourse on the interplay between digitalization and sustainability and, to a lesser degree, tweets that address issues outside the European context. Thus, we trained a binary text classifier using the natural language processing framework *spacy*, implemented in Python, to filter relevant tweets (Montani et al. 2022). The classifier makes use of the pretrained transformer model *distilroberta* (Liu et al. 2021).

To train the classifier, a team of three coders first manually annotated a gold standard evaluation set of 600 randomly sampled tweets (400 from *sus_digi_eu*, 200 from *sus_eu*), based on an initial codebook. By comparing and resolving differences among coders, we then created a final codebook and a test set, which was held back from training. A further 586 randomly sampled tweets from *sus_eu* were additionally added to this test set based

1 Computer code and access to tweet IDs to reproduce the analysis presented here is available at a public repository at *https://doi.org/10.5281/zenodo.7555375*.
The access to tweet IDs is in accordance with Twitter's developer policy regarding content redistribution at *https://developer.twitter.com/en/developer-terms/policy* (as of 26 April 2022).
2 2010 can be seen as the start of a phase for Twitter in which the microblogging platform added several crucial functions raising its popularity.

on the final codebook. Adding more samples from *sus_eu* ensured a robust evaluation set that is more representative of the *sus_eu* target set.

In the final codebook, we chose to be relatively inclusive by treating the co-occurrence of explicit sustainability and digitalization mentions as necessary and sufficient for accepting a tweet. At the same time, we specified two explicit exclusion criteria: first, the tweet could not use "sustainable" explicitly in the sense of "long-term" or "enduring." Without an explicit qualification, we considered the mere use of "sustainable" to be sufficient, as we judged this to give the actors participating in the discourse the benefit of the doubt regarding their use of the sustainability terminology, preventing us from imposing our own ontological stances about sustainability concepts. Second, a tweet could not refer explicitly and solely to an issue outside the European context and without European involvement. If no geographical location was mentioned explicitly, we accepted the tweet.

Based on the final codebook, we coded a training set of 3,841 tweets from the *sus_eu* dataset to train the classifier. Classes in the large *sus_eu* dataset were highly imbalanced, which led us to emphasize precision over recall in training the classifier, because in the presence of a large imbalance in our dataset, low precision would quickly result in a significantly high number of false positives. Currently, the classifier achieves a precision of 0.85 on the evaluation set and a recall of 0.69, leading to an F1 score of 0.76. Applying the classifier to the *sus_eu* dataset yielded a dataset of 34,802 tweets. Given our relatively low recall on the test set, the true total number of tweets relevant to the discourse is likely higher, while we can be relatively more confident – given our emphasis on precision – that the tweets we identify are truly relevant.

Step 2: Inductive identification and rule-based classification of domains in tweets

To identify inductively the discourse domains after initial filtering, we follow an approach inspired by what Carlsen and Ralund (2022) call computer-assisted text analysis, a variant of computational grounded theory. Following the workflow terminology of Carlsen and Ralund (2022), in a qualitative *discovery* step, we utilized our immersion into the corpus gained by annotating the first binary classifier to derive inductively a set of domains and to assign non-overlapping, single-, and multi-word search terms to them. We then extended these search terms by incorporating suggestions of similar single- and multi-word terms based on *sense2vec* (Trask et al. 2015). A common practice on Twitter is the use of so-called hashtags, which often combine multiple words into one string (e.g., "smart city" becomes "#smartcity"). We accounted for this by combining all our multi-word searches into single words, in addition to multi-word patterns.

In a *grounding* step, we then applied the search terms and explored them in context, updating them along the way and refining the domain set. We iterated in this way over five main rounds, arriving at a final set of 29 discourse domains and associated search terms. In a classification step, we then assigned domain labels to tweets using a rule-based model based on our search terms.

Step 3: Zero-shot classification of transversal discourse dimensions economic growth and efficiency

We evaluated tweets related to the discourse concerning whether they referred to two broader transversal discourse dimensions (i.e., spanning domains). We focused on the following two dimensions: reference to economic growth, which we also further qualitatively assessed concerning stances taken in tweets (a supportive or critical stance towards economic growth) and references to (resource) efficiency and sufficiency considerations. To classify these transversal dimensions, we relied on a zero-shot classifier trained on the *MultiNLI* dataset (Williams et al. 2018), and tweets were preprocessed for the zero-shot classifier following Gambini et al. (2022). We evaluated the performance of each classification against test sets of tweets annotated by a team of four annotators[3].

Contextualization of domain presence

To move beyond the description of domain occurrence and cooccurrence over time, we were interested in identifying potential causes of the spikes in certain domains during the period of analysis. To do so, we followed a qualitative explorative approach in conducting desk research. First, we used a search engine, Google, with the keywords related to the key domains within the period in which they were mostly present and with the qualifier "Europe". Relevant hits were scrutinized and screened as to whether they dealt with the respective domains and Europe in the given timeframe. Second, because actors related to the European Union (EU) were behind a predominant number of accounts in the tweets analyzed, we also searched the website of the EU with the respective keywords to identify events, programs, or other external factors related to the domains. Our findings are presented as hypothetical explanations of the presence of dominant domains in our dataset over time.

Results

Domains over time: Dominant domains and developments

Table 1 (p. 14) lists the 29 domains we inductively identified and around which the discourse on Twitter revolved, including the labels assigned to them, which were used in visualizations in this article. Figure 3 (p. 15) shows the relative presence of domains in the discourse between 2010 and 2021. Some domains are stable components of the discourse over the decade in our analysis. Smart city concepts (SMC) and mobility (MOB) are present in the top 5 in every year, and discussions of them in terms of their relative weight in the discourse peaked mid-decade. The joint

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3 Economic growth classifier: Matthew's correlation coefficient (MCC) 0.67, balanced accuracy (BA) 0.85. Economic growth support: MCC 0.54, BA 0.79. Efficiency: MCC 0.58, BA 0.79.

TABLE 1: Domains identified in the English-language discourse on sustainability and digitalization in Europe on the social media platform Twitter between 2010 and 2021.

DOMAIN	LABEL
agriculture	AGR
air travel	AIR
biodiversity	BIO
blockchain technology	BLO
construction	BUI
circular economy	CIR
climate change	CLIM
recovery/COVID	COV
cultural heritage	CUL
data center	DAC
energy transition	ENE
EU programs	EUP
fashion	FAS
finance/economy/investments	FIN
fishing/ocean	FIS
forestry	FOR
health	HEA
smart home	HOM
green information and communication technologies	ICT
manufacturing	MAN
transport/mobility	MOB
future of work	OFF
pollution/waste	POL
raw material use	RES
smart city	SMC
small and medium enterprises	SME
smart village	SMV
tourism	TOU
water supply	WAT

presence of mobility and smart city concepts is likely because discussions of how to make cities "smart" often focus on sustainable forms of mobility. As such, the mobility domain intersects with the smart city concept domain to an extent. The predominant presence of smart city concepts and mobility between 2010 and 2021 could be explained by the European *Smart Cities Marketplace* program, the first EU publication, dating to 2010. Data centers (DAC) and sustainable ICT domains were much more prominent at the beginning of the decade, when the usage of cloud data storage and computing became widespread. Only in 2021 did data centers again gain prominence in the discourse, which might have been guided by the European data strategy, initiated in 2020.

In fact, energy (ENE) is another constant domain related to the discourse that remained in the top 5 until 2020. Akin to the other domains, energy has been a prominent theme discussed in Europe, spearheaded by the introduction of the *Energy Union Strategy* in 2015 (EC 2015), a key priority of the Juncker Commission (2014 to 2019). The most rapid increase in prominence in the latter half of the decade relates to the discussion of climate change (CLIM) since 2017/2018 and finance (FIN) since 2020. The high prevalence of climate change since 2015 is likely related to the accomplishment of the *Paris Agreement* in 2015, the more frequent releases of UN Intergovernmental Panel on Climate Change (IPCC) reports since 2018, and the more general increase in awareness of climate change in the wake of the *Fridays for Future* protests in Europe since 2018. The fact that the finance domain has been one of the main domains since 2019/2020 could be related to the EU-wide discussions of the EU taxonomy, a framework for sustainable investments in Europe and parallel developments in fintech (financial technology).

We can also analyze the stability and developments of domains by comparing domain occurrences in each year in relation to the previous year. Figure 4 (p. 16) shows such trend lines for every domain, emphasizing dominant domains in the yearly discourse using transparency and line width, as large swings in presence are much more likely among domains with few mentions. Further, this normalization regarding the relative weight of a domain in the overall discourse each year adjusts for the overall increase in tweets in general in our dataset over the analyzed period. Some striking results include the introduction of blockchain technologies (BLO) in 2018, which can partly be explained by the explosion of Bitcoin, Ethereum, and Litecoin transactions in the same year. Further, the large upswing in the health domain (HEA) in 2016 could be related to the publication of the seminal biannual report *Health at a Glance* by the Organisation for Economic Co-operation and Development (OECD) and the EU the same year, wherein the concept of sustainable health systems in Europe was mentioned for the first time.

Similarly, tourism (TOU) experienced an uptick in 2013 and again in 2018, where the latest increase could be explained by the *European Capitals of Smart Tourism* award, which was first handed out in 2018 and which was prominently tweeted about in our dataset. In 2017, we can identify the introduction of the agriculture domain (AGR), which is likely related to the strategic approach to EU agricultural research and innovation presented in Brussels in 2016, highlighting the potential of technology for sustainability in the farming sector and rural areas. In comparison, we observed a large increase in the presence of the EU-level program (EUP) domain in 2019 and 2020, which might be a result of the announcement and implementation of the EU digital agenda, the *European Green Deal,* and the Covid recovery plan, all of which emphasized exploiting the interplay between digitalization and sustainability.

Transversal discourse dimensions

Results concerning the occurrence of our transversal discourse dimensions differ substantially between dimensions. Of all tweets labeled as dealing with economic growth (ca. 3%), 88% were labeled as taking a positive or supportive stance, while the remainders were inconclusive. There are so few critical stances toward economic growth that a meaningful analysis of its presence in the discourse was not possible (even though the few labeled examples generally illustrate that the classifier could identify them, albeit with low precision). For efficiency considerations, we find 4.6% of tweets classified as containing efficiency content, which is a sizable proportion of the discourse, especially

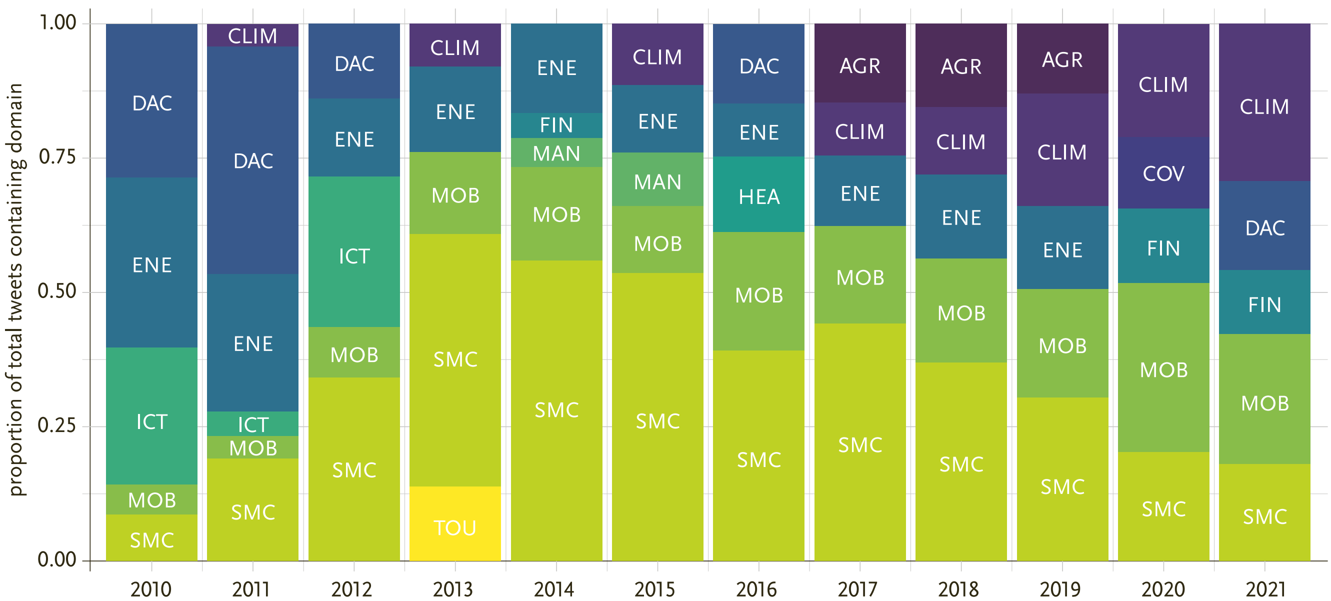

FIGURE 3: Top five domains per year (relative presence) in English-language tweets relating to the discourse on sustainability and digitalization in Europe between 2010 and 2021. In 2011, domains MOB and CLIM share place 5, because they had exactly the same number of tweets. See table 1 for domain label reference.

given that our classifier has relatively low recall on our test set and, as such, likely underestimates the true number of efficiency-related tweets. We also find about 0.05 % of tweets classified as sufficiency related, which is, however, primarily due to the presence of self-sufficiency considerations in the smart rural topic. Thus, as with critical stances toward economic growth, sufficiency in a broader sense is likely mostly absent from the broader Twitter discourse.[4]

Interrelation among domains: The discursive landscape

Some discourse domains are discussed in relation to each other more often than others. As such, the overall discourse on sustainability and digitalization in Europe can be seen as a network of interrelated domains, some of which cluster together to form sub-discourses that go beyond single domains. Analyzing domain interrelations in this way provides a more high-level overview of the evolution of the discursive landscape or discourse topology. We analyze domain interrelation by analyzing how often domains co-occur in the same tweets. Figure 5 (p. 17) illustrates such co-occurrences in the empirical example of the second- and fourth-most liked tweets in our datasets.

Figure 6 (pp. 18 f.) shows a network visualization of domain co-occurrences over three phases. We assigned a phase each to the years between 2011 and 2014, between 2015 and 2019 (pre-pandemic), and between 2020 and 2021 (pandemic). We normalize counts of co-occurrences for every domain in the symmetric co-occurrence matrix, which accounts for the imbalance in domain occurrences and treats variations in every domain independently of its absolute occurrence. Figure 6 displays up to the ten most frequent co-occurrences (top ten co-occurrences) a domain has with other domains for every domain. This co-occurrence graph is an indication of a higher-level structure within the overall discourse, and we clustered domains within the graph using modularity[5] maximization (Brandes et al. 2008).

Discussion

In this study, we analyzed the public discourse on the interrelationship between digitalization and sustainability on Twitter between 2010 and 2021. Our goal was to identify the main domains discussed in the discourse, to sketch the development and drivers of these domains and their interrelationship over time, and to investigate the discourse for the presence of key transversal elements highlighted in the fields of academia and policy. Some domains were specifically prominent in certain years but were not consistently discussed during the period under study. A likely explanation for such punctuations in attention were external factors, such as political issues or events, programs, or social movements (cf. Downs 1972) as highlighted in the contextualization of our results. Confirming previous research (Marenco and Seidl 2021), the results of the contextualization of the domains, as well as the dominance of EUPs as a discourse since

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4 For similar findings in the research community see Santarius and Wagner (2023, in this issue) and in the economy see Gotsch et al. (2023, in this issue).
5 Modularity is a quality measure for clusterings: by maximising modularity a graph is subdivided in groups (clusters) that have a maximum number of within-group interrelations and a minimum number of external relations. For the calculation procedure see Brandes et al. (2008).

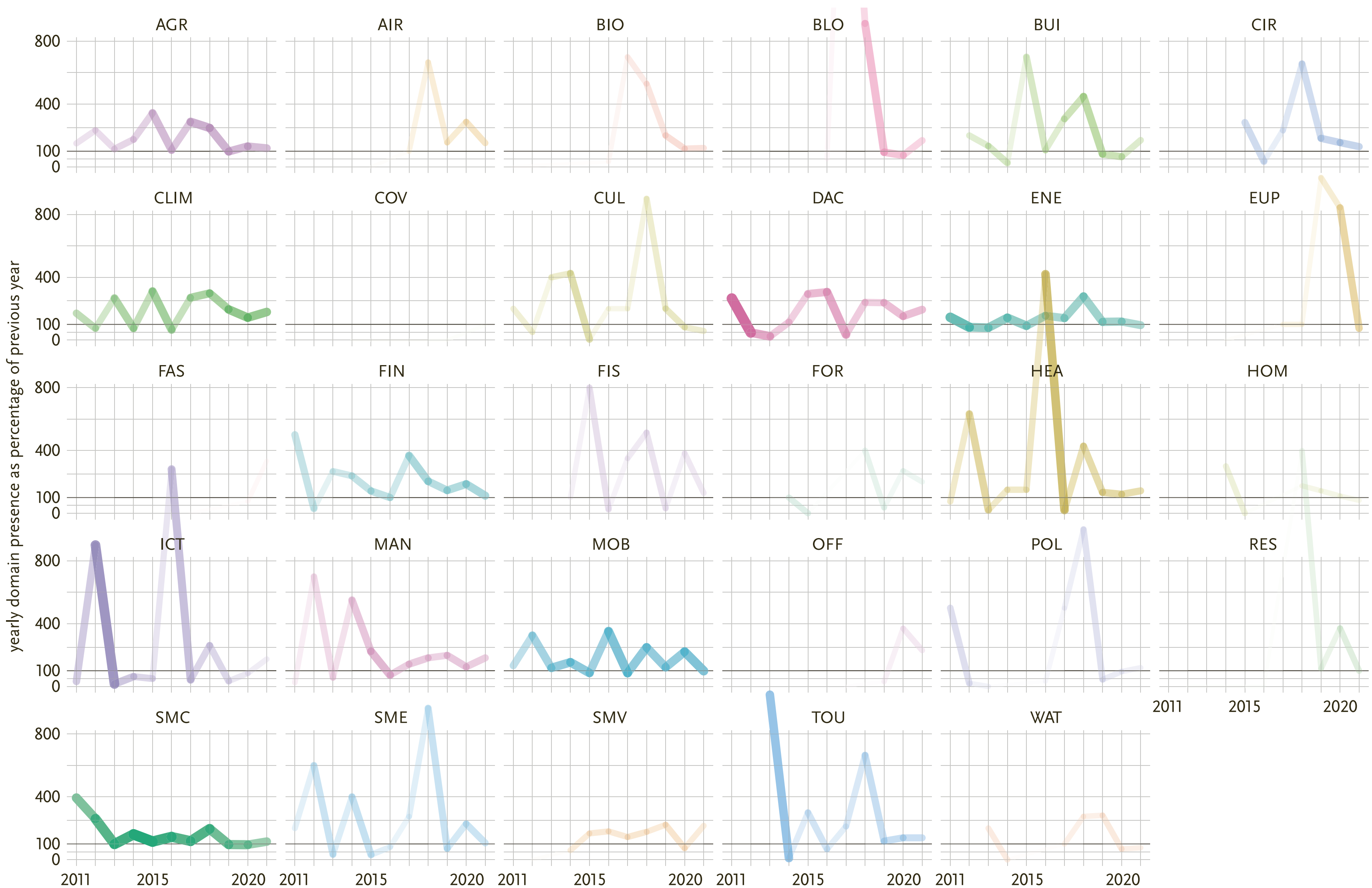


FIGURE 4: Trends in domain occurrence for each domain in English-language tweets relating to the discourse on sustainability and digitalization in Europe between 2010 and 2021. Line inflection points denote changes in yearly mentions of the domain as a percentage of mentions in the previous year. Transparency and width of lines relate to the share of all domain mentions a specific domain received in a given year (at the line inflection points). Reading example: The domain ICT made up a relatively large proportion of the overall discourse in 2012 and 2013 (wider and more solid line); it saw a large spike in attention in 2012 and 2016, compared to previous years (line inflection points). See table 1 for domain label reference.

FIGURE 5: Illustration of domain identification and domain co-occurrence in tweets.

2018, reinforce the impact of institutions, such as the EU, and thus, the political and regulatory power that structures can exert over public discourses on sustainability and digitalization.

In addition, the co-occurrence analysis of domains (figure 6) has allowed us to distinguish tentatively three phases in the Twitter discourse on sustainability and digitalization in Europe over time. The first phase of the discourse at the beginning of the decade centered much more strongly on the life-cycle impacts of digital technologies and was dominated by smart city concepts, as compared to the later stages.

The second phase, in the second half of the decade until the COVID-19 crisis, saw a second discursive hub emerge surrounding climate change. Two additional sub-discourses were identified, one connecting energy use both with digital infrastructure and the potential of smart grid technologies and a second concerning the potential for sustainability gains through digitalization in manufacturing and circular economy concepts.

During the COVID-19 crisis years, the third phase, climate change emerged as the dominant central discourse, being discussed based on a variety of domains. A distinct "smart rural" cluster also emerged during this time, including smart agriculture, forestry, and issues specific to digitalization in rural regions, such as broadband connectivity. The life-cycle impacts of digitalization were also being discussed again, as data centers were more frequently discussed in conjunction with energy use and climate impacts, as well as pandemic-induced changes in working patterns.

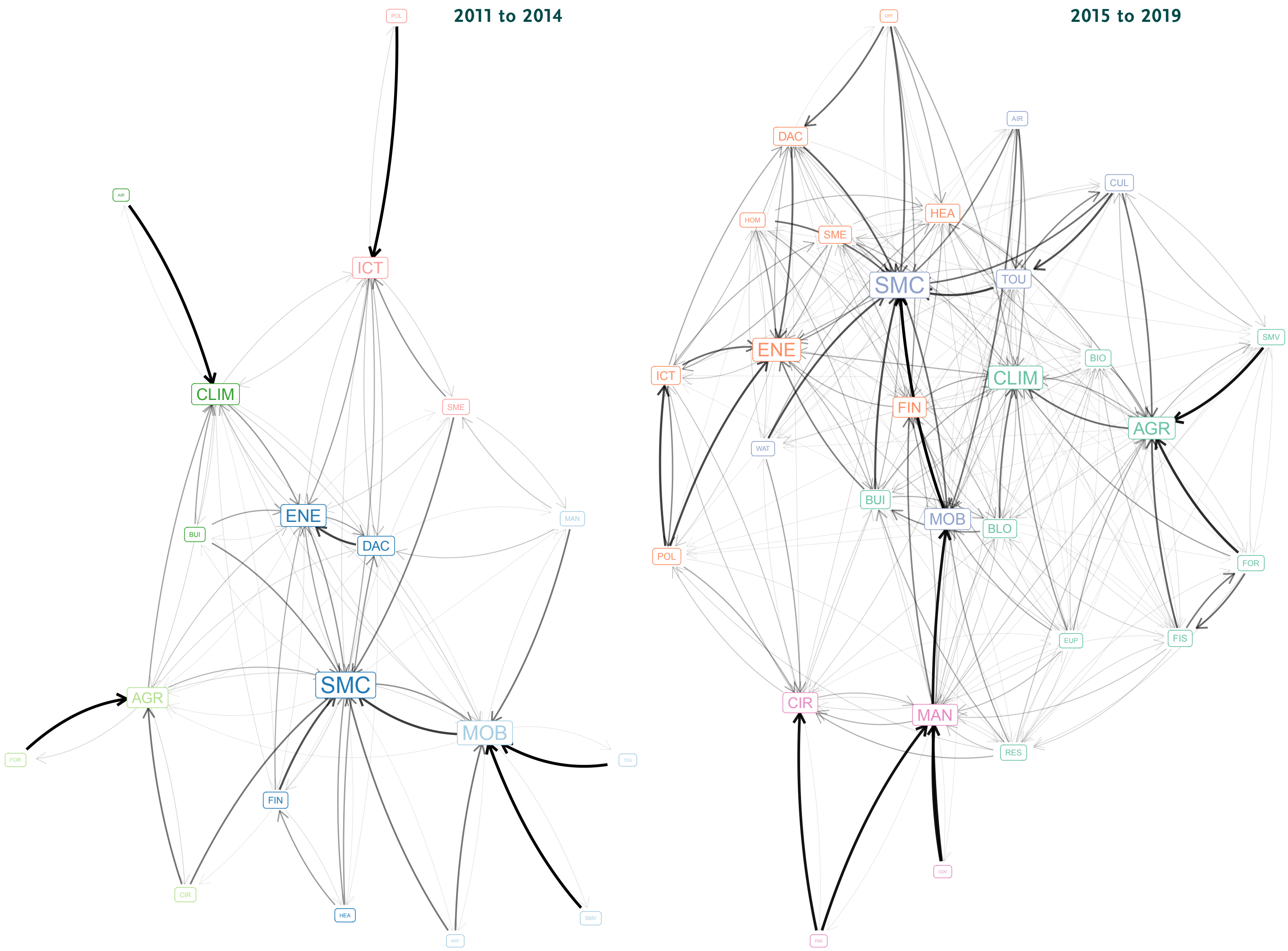
Limitations

Our analyses of tweets from 2010 until 2021 are, of course, only a snapshot of the public discussions of sustainability and digitalization. Furthermore, beyond domain identification, we did not conduct an in-depth analysis of the presentation of the respective domains in terms of valence or arguments brought forward against or in favor of the current state of digitalization in the domain. Another limitation of our approach might be that we have missed possible additional domains that were not identified in the qualitative discovery step. Regarding our classification step, we are confident that our rule-based approach has a relatively high precision in classifying domains, but it faces limitations in recall that could potentially be resolved using a statistical model for classification, though at the cost of increased complexity. Furthermore, we feel it is important to re-iterate that Twitter is a biased and flawed data source for understanding societal discourses in many aspects. As such, to generate a more encompassing map of the societal discourse, future work complementing ours would need to consider other mediums and fora in which discourse manifests, beyond elite discourses on specific social media platforms.

Conclusion

This study aids in our understanding of how the discourse surrounding two of the most crucial socio-technical change processes of our time in Europe (and globally) – that is, sustainability transformations and digitalization – have evolved in the past decade. We were able to chart the development of a multi-faceted discourse using a multitude of domains over a decade, from concerns about the life-cycle impacts of ICT technology, to the rise in prominence of smart cities, to the establishment of climate change as a key discursive hub. Our results regarding domain clusters in the discourse point to potentials and the crucial importance of nexus approaches – which do not consider domains in isolation – in the research on and practices of digitalization and sustainability.

What does appear in the discourse is as interesting as what does not appear in our analysis, which comes upon the eve of the recent *Digital Reset* report by Digitalization for Sustainability (D4S 2022). We find the discursive structure very much in line with some of the concerns about the direction of digitalization raised in the report, namely, an over-reliance on efficiency justifications to champion digitalization accompanied by little critical reflection on economic growth or mention of sufficiency strategies. We also find an almost total absence of discussions on the structural impacts of digitalization on sustainability (Hilty and >



Aebischer 2015), such as those brought about by big tech companies' pressure on regulatory environments (Andersen 2021). In this way, as a complement to conceptual reflections and empirical assessments of sustainability and digitalization, our results offer a possibility for research in this area to reflect the differences between societal and academic discussions. In some recent, quickly developing domains (e.g., finance or blockchain technologies), sustainability research should interpret our results as a call for increased research on these domains and for researchers to assert themselves more forcefully in the societal discourses surrounding them. In our opinion, our results further imply a normative responsibility of researchers to improve awareness of underrepresented topics in the critical discourse beyond academia. In addition, there is a need for more discussions of structural changes to the conditions for sustainability due to the power of big tech, the importance of sufficiency strategies, and the actual value of efficiency arguments in the discourse surrounding sustainability and digitalization.

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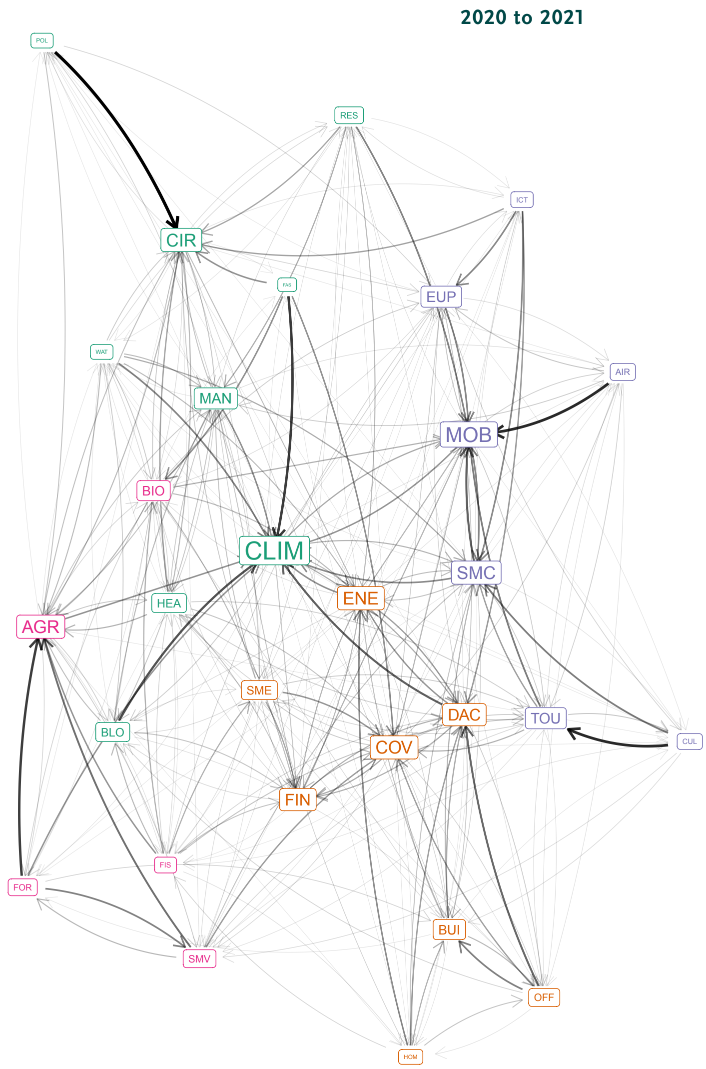

FIGURE 6: Interrelations of domains based on co-occurrences of domains in English-language tweets relating to the discourse on sustainability and digitalization in Europe across three phases between 2011 and 2021. The thickness of an arrow pointing from one domain i to another domain j is based on the number of co-occurrences *i* has with *j* as a percentage of *i*'s co-occurrences with all other domains. For every domain, the top ten co-occurrences are shown (if the domain has as many). Domains are sized by their overall number of co-occurrences. Domains were clustered by maximizing modularity (Brandes et al. 2008). Elements of the same cluster have the same color. See table 1 for domain label reference.

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Digitalization and sustainability: A systematic literature analysis of *ICT for Sustainability* research

Close scrutiny of the ICT for Sustainability *conference proceedings on digitalization and sustainability reveals a bias on (technological) efficiency solutions. This bias is mirrored in blind spots in the public discourse and the political debate. The sustainable transformation of society calls for more comprehensive research – and research funding – to fill the gaps and integrate efficiency, consistency, and sufficiency strategies on the levels of life-cycle, enabling, and structural effects.*

Tilman Santarius, Josephin Wagner

Digitalization and sustainability: A systematic literature analysis of *ICT for Sustainability* research
GAIA 32/S1 (2023): 21–32

Abstract
In order to govern processes of digitalization for the purpose of the common good, it is important to understand the opportunities and risks of information and communications technology (ICT) for a sustainable transformation of society. In this article, we systematically review 215 publications from the *ICT for Sustainability (ICT4S)* conference corpus in order to investigate the state of debate. We analyze to what extent research covers sustainability implications of ICT, 1. regarding different levels of actions and effects, as well as 2. regarding the three different strategies of sustainability – efficiency, consistency, and sufficiency. We find that *ICT4S* research has a one-sided focus on digital efficiency improvements and on life-cycle impacts of ICT devices and applications. There is far less research on digitalization's potential to advance sufficiency-oriented practices, and questions of how to foster digital sustainability transformations at macro- and structural level are only marginally treated. We draw conclusions for funding and science politics.

Keywords
consistency, digitalization for sustainability, efficiency, enabling effects, ICT for sustainability, knowledge transfer, life-cycle effects, literature review, structural effects, sufficiency, sustainability strategies

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The ambiguity of digitalization for sustainability

There is growing recognition within society and academia of the importance to understand the impact information and communications technology (ICT) has on efforts towards a sustainable transformation of society. In this article, we focus on the environmental dimension of necessary sustainability transformations with the main aim to avoid transgression of planetary boundaries, prevent further violation of critical Earth-system processes, and ensure the premises for decent living within humanity's safe operating space (Rockström et al. 2009, Steffen et al. 2015, Fuchs et al. 2021).

The role of ICT in sustainability transformations appears to be ambiguous. One the one hand, digitalization is argued to offer opportunities, for example, by way of resource and energy efficiency improvements, process optimizations, and substitution of physical by virtual consumption. On the other hand, research is concerned with environmental risks that accompany digitalization, for example, the growing volume of resource and energy demands and emissions from the production of ICT hardware and operation of software as well as negative indirect effects such as rebound or reduction effects or malevolent forms of substitution that increase resource and energy intensities (see, e.g., Hilty 2008, Börjesson Rivera et al. 2014, Santarius et al. 2020).

Research on opportunities and risks of ICT for sustainability transformations is conducted in many disciplines and published in various different media and journals (Lange and Santarius 2020). The research community *ICT for Sustainability (ICT4S)* with its recurrent *ICT4S* conferences since 2013, including several hundreds of peer reviewed publications in *ICT4S* proceedings and elsewhere, provides a particular mirror of the wide-ranging state of research on digitalization and sustainability (see, e.g., Hilty and Aebischer 2015, Chitchyan et al. 2020). In this article, we investigate all publications from the *ICT4S* conference corpus between 2013 and 2019 in order to assess the state of debate regarding the role of ICT in sustainability transformations.

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More specifically, we conduct a systematic literature review in order to investigate two overarching questions. First, we analyze whether the conference proceedings cover risks and opportunities of ICT for sustainability on different levels of actions and effects – namely, regarding life-cycle effects of devices, enabling effects, and structural effects. Second, we investigate whether the three basic sustainability strategies – namely, efficiency, consistency, and sufficiency – are treated on equal terms in the *ICT4S* proceedings.

Our respective assumptions are, for one, that, from a sustainability perspective, action is needed on all levels in order to truly achieve transformative change in society (Geels 2011, Santarius 2015). For instance, there is little doubt that digitalization can reduce energy and resource demand as well as emissions at the life-cycle level regarding certain products and services. This has been shown in many case studies, for example, by comparing e-books with print books or video streaming with conventional DVD watching (Lüders et al. 2021). However, environmental improvements at the micro-level can be countervailed at the macro-level, for instance, when sales of print books remain at high levels despite additional e-book demand, and people watch more hours on video-streaming and TV altogether than compared to before the advent of streaming.

Secondly, we assume that all three basic sustainability strategies need to be addressed in order to not merely achieve 'ecological modernization' or an optimization of the status, but to achieve deep transformations (Sachs et al. 1998, Geels et al. 2017). For instance, relative efficiency improvements need to be accompanied by absolute reductions as well as by a change in the resource base towards renewable materials and energy carriers. More specifically, sufficiency is needed not only to ensure an absolute decrease in energy or resource consumption, but also to counteract possible rebound effects from efficiency improvements (Herring 2009). Consistency strategies integrate production and consumption processes in natural life cycles and thereby minimize leakage effects or negative spill-over effects between different environmental domains and indicators (Jaeger-Erben et al. 2021). Hence, it is not only important to systematically understand – and develop concurrent strategies – how ICT can advance efficiency improvements, but also how ICT can enable and advance sufficiency and consistency strategies.

A previous study by Mann et al. (2018, p. 222) attests the work of the *ICT4S* research community to be "unfortunately, insufficient to deliver a meaningful change towards a regenerative socioecological transformation". Using the Mann-Bates maturity scale for sustainability, the researchers analyzed the conference corpus to measure how mature the research of the *ICT4S* community is with regard to sustainability. The results of our literature review are more nuanced, but overall, they confirm the critical assessment of the state of debate. We find that the current *ICT4S* discourse has a rather narrow focus on digitalization's opportunities and risks for sustainability transformations. Publications do not cover aspects of sufficiency and consistency as much as aspects of efficiency. And they do not address structural effects as much as life-cycle and enabling effects. Based on the results, our article will formulate main research needs and lessons-learned for policy-making, including funding policies. More specifically, our article will discuss how the particular 'blind spots' of research regarding the transformative potential of ICT in various sectors can be addressed.

A systematic literature review of *ICT4S* research

To assess the state of research on digitalization's opportunities and risks for sustainability transformations, we conduct a systematic literature review of publications from the *ICT4S* conference corpus. We are aware that this selection is neither exhaustive nor representative of all global publications on the issue. However, we consider the publications of the *ICT4S* conferences as a particular mirror of the state of debate. The "ICT4S conferences bring together leading researchers in Information and Communications Technology (ICT) for Sustainability", and *ICT4S* is the only international scientific conference series that claims "to identify and respond to grand challenges in the interplay between sustainability and digital technologies" (Penzenstadler and Easterbrook 2018, preface). Note that it is a highly inter- and transdisciplinary research community, covering disciplines such as informatics, computer sciences, engineering, but also sociology, psychology, economics, as well as future studies, marketing, and other disciplines. Moreover, the *ICT4S* research community integrates members from civil society and business, for example, scholars from Ericson or Telecom who provide trend analyses on energy demand of communication networks from first hand data, for instance (see, e. g., Malmodin 2020, Malmodin and Lunden 2016).

Our literature review covers the proceedings of all six *ICT4S* conferences that took place between 2013 and 2019 (our analysis was finalized by the time the 2021 proceedings were formally published). In total, 215 *ICT4S* conference papers were analyzed.[1] Given the two overarching research questions outlined above, publications were classified along two dimensions. The first dimension is based on the LES model introduced by Hilty and Aebischer (2015). This model conceptualizes the impacts of ICT on society and environment on three connected levels: life-cycle effects, enabling effects and structural effects. Hilty and Aebischer (2015, pp. 27–30) define the potential effects as follows:

1. ***Life-cycle effects*** are "caused by the physical actions needed to produce the raw materials for ICT hardware, to manufacture ICT hardware, to provide the electricity for using ICT systems (including the electricity for non-ICT infrastructures, such as cooling), to recycle ICT hardware, and finally to dispose of non-recycled waste" (Hilty and Aebischer 2015, p. 27).

1 A complete list of all 215 *ICT4S* conference papers analyzed in the systematic literature review is available online at *https://conf.researchr.org/series/ict4s*. *ICT4S* conference papers cited in this article are integrated in the references.

TABLE 1: Number of identified conference papers per level of the LES model and sustainability strategy. Note: Conference papers are double counted if they address more than one level and strategy. If papers treat issues that cannot be assigned to one of the sustainability strategies, they are labelled as "other".

LEVEL	LIFE-CYCLE EFFECTS				ENABLING EFFECTS				STRUCTURAL EFFECTS			
number of papers	66				111				34			
sustainability strategy	efficiency	sufficiency	consistency	other	efficiency	sufficiency	consistency	other	efficiency	sufficiency	consistency	other
number of papers	45	11	8	12	67	33	21	26	18	7	0	12

2. ***Enabling effects*** refer to actions that are enabled by the application of ICT. These actions can be understood as optimizing production, consumption or technical processes, as media substitution (e.g., replacing printed documents with electronic documents) and as externalizing of control over a process or system.
3. ***Structural effects*** refer to actions enabled by ICT that lead to changes in economic structures and institutions. "Institutions, in the wider sense, include anything immaterial that shapes action, that is to say law, policies, social norms, and anything that can be regarded as the 'rules of the game'" (Hilty and Aebischer 2015, p. 30).

For the second dimension of classification, our analysis is guided by the three basic sustainability strategies: efficiency, consistency and sufficiency (Sachs et al. 1998). For the purpose of this paper, we briefly define the three strategies as follows (for more nuanced definitions of these strategies in the context of digitalization, see Santarius et al. 2022):

1. ***Efficiency*** is understood as any strategy aimed at reducing the *relative* energy or material input per unit of production or consumption; that is, the (technical) ratio between inputs and consumption or production level. Note that considerations of rebound effects as a potential effect of efficiency improvements have been assigned to the category of efficiency as well.
2. ***Consistency*** is understood as any strategy aimed at using renewable energies and materials and at closing nutrient cycles. In a broader sense, strategies for consistency are aimed at achieving a circular economy.
3. ***Sufficiency*** is understood as any strategy aimed at decreasing the *absolute* level of resource and energy demand by way of rethinking needs or changing consumption and production habits or patterns (e.g., by way of sharing practices or by changing the modal split in mobility).

Following Mayring (2014), these definitions serve as theoretical deductive root categories for our literature review, and they provide a coding guide to structure our analysis. As a first step, one researcher read abstracts to broadly classify the articles according to levels of effects and sustainability strategies. In the majority of the papers, as a second step, full texts were read to validate the initial classification. As a third step, a second researcher read a random sample of abstracts to double check the classification. Discrepancies in classification were discussed between the two researchers to identify and address any structural differences in classification.

In our analysis, differentiation of the three sustainability strategies was set in relation to the type of effects according to the LES model. Note that we neither treat types of effects nor sustainability strategies as exclusive silos, but that a significant number of conference papers have been found to address more than one type of effect and more than one sustainability strategy. Accordingly, table 1 lists double-counted conference papers that address multiple strategies or effects. Conference papers were numbered and sorted in a table that distinguishes LES levels and sustainability strategies (table 1).

In addition to the classification of conference papers along the two dimensions, structural coding was conducted by one researcher to explore and identify research topics addressed in the conference papers (Saldaña 2013, p. 84). In an iterative process of analytical memo writing and discussing emergent topics with the second researcher who read pre-selected papers, identified research topics were re-categorized and eventually mapped to research clusters, with at least five conference papers qualifying a topic to be considered a research cluster. The research clusters were mapped against the LES levels and sustainability strategies (figure 1, p. 25).

Hot spots and blind spots in the *ICT4S* conference papers

Our systematic literature review delivers deep insight into thematic hot spots but also the blind spots of literature on ICT for sustainability. Table 1 shows the number of conference papers identified per level and sustainability strategy. Note that research endeavours can be multidimensional and thus address more than one level and strategy. In fact, out of the 215 analyzed conference papers, 51 address two or more strategies or levels and 27 could not be assigned to any of them. Accordingly, conference papers have been double counted when addressing more than one level or strategy. The following subsections give an overview of key topics identified per level, starting with the level including the most conference papers and closing with the level including the least.

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Level of enabling ICT effects

As table 1 shows, the *majority of conference papers (n = 111) investigate enabling effects of ICT*. Taking into account the three sustainability strategies, 67 of those conference papers focus on efficiency. 33 conference papers focus on sufficiency, and 21 focus on consistency. 27 conference papers bound to the level of enabling effects address more than one sustainability strategy.

Further analysis shows that the focus on *efficiency* in the majority of the conference papers refers to the provision or use of energy. For instance, research looks at various ICT solutions for optimizing energy supply in electricity grids (Uslar and Masurkewitz 2015, Hinrichs et al. 2015) or digital infrastructures for the grid-wide balance between energy demand and supply. Examined infrastructures are, for example, (renewable) energy trading platforms (Wagner vom Berg et al. 2016, Murkin et al. 2016) or a blockchain technology for efficient trading of renewables (Mihaylov et al. 2016). Balancing energy demand and supply per household (Brito et al. 2016, Schien et al. 2019) or site via demand shifting is another approach researchers examine in terms of efficiency, such as how to optimize the workload placement of a multi-site cloud provider by migrating its energy consumption to countries with the lowest carbon intensity of electricity (James and Schien 2019).

On the user side, research explores ICT-supported energy efficiency strategies in data centres (Procaccianti and Routsis 2016), households and buildings (Schien et al. 2019, Shafqat et al. 2019, Denward et al. 2015, Tabatabaei 2016, Georgievski and Bouman 2016, Beucker and Hinterholzer 2019, Li et al. 2013), cities and neighbourhoods (Svane 2013, Blöchle et al. 2013, Kramers et al. 2013, Al-Anbuky 2014), and offices (Lou et al. 2019). A recurrent theme is feedback from ICT devices and applications to users regarding their energy consumption with the potential result of fostering energy efficient behaviour (Weeks et al. 2014, Jakobi and Stevens 2015 a, b, Kamilaris et al. 2015, Shafqat et al. 2019, Lou et al. 2019, Schien et al. 2019, Price et al. 2013, Tabatabaei 2016, Knoll et al. 2016 b, Johnson et al. 2013). Other conference papers focus on ICT-based feedback for the efficient use of water (Anda et al. 2013) or the efficient handling of waste (Nyström et al. 2018). Another topic frequently discussed is whether and to what extent ICT can support retrofitting of houses in order to increase energy and resource efficiency (Massung et al. 2014, Weeks et al. 2015, Sabet and Easterbrook 2016). Some conference papers deal with ICT-based efficiency solutions and related greenhouse gas savings (Williams et al. 2013, Malmodin and Bergmark 2015, Coroama and Höjer 2016) and with ICT applications that support efficient process designs in different contexts such as e-waste recycling (Franquesa et al. 2015), waste collection (Shahrokni et al. 2014), environmental information systems (Thies and Stanoevska-Slabeva 2013) and reporting (Mora-Rodriguez and Preist 2016), as well as food sharing (Katzeff et al. 2019).

Out of the 111 conference papers that investigate enabling effects, 33 conference papers address *sufficiency*. The most prominent issue (11 conference papers) refers to energy consumption in households and ICT solutions that support sufficient behaviour of occupants, for example, by spurring reflection and discussion on energy consumption using an "ambient information display" to visualize indoor temperature (Hedin et al. 2018). Denward et al. (2015) look at how offers from energy suppliers to manage energy efficiency in apartment buildings with the help of ICT also lead to discussions on comfort expectations and social practices related to the concept of comfort – and often also to the lowering of indoor temperature levels. In the context of sufficient energy consumption, another focus is on the extent to which ICT-supported feedback on energy use and energy supply helps users adapt their household routines to the availability of renewable energy (also in the context of prosuming: Price et al. 2013, Ferrario et al. 2014, Barreto et al. 2019 and via pricing Brito et al. 2016). Sufficiency strategies possibly supported by ICT are, for example, shifting activities over time (Bourgeois et al. 2014), sharing oversupply of self-generated energy within the community, or carrying out alternative, less energy-intensive activities (Ferrario et al. 2014).

The second most prominent topic (6 conference papers) is ICT-supported sufficiency in mobility. These conference papers deal with how ICT provides users with information enabling them to use more sustainable transportation modes, such as public transport, ridesharing, or rental bikes (Viktorsson 2013, Gieselmann et al. 2013, Nyblom and Eriksson 2014). One conference paper deals with information from ICT applications to decision makers in rural municipalities so that they can consider specific mobility needs and lifestyles of different socio-demographic groups in their mobility planning process with the goal of enabling all groups to access sustainable transportation modes (Knoll et al. 2016 a). Kramers et al. (2015) look at how emerging ICT tools can reduce travelling altogether by decentralizing workplaces into work hubs, while Weiser et al. (2015) investigate the circumstances for components such as ICT-based feedback and game elements to afford user motivation toward changes in personal mobility behaviour. A third topic (4 conference papers) deals with ICT that supports self-organizing processes, with the focus more generally on community-level effects (Lukács 2013, Gui and Nardi 2015) or on sufficient practices within communities, such as food sharing (Katzeff et al. 2019) and mapping for urban farming (Walker and Becker 2016).

Of the 111 conference papers investigating enabling effects, 21 conference papers address aspects of the *consistency* strategy. The majority examine ICT-supported transition from fossil fuels to the use of renewable energy (which in itself can be understood as consistency strategy) and thereby also address efficiency and sufficiency strategies described above in relation to energy use and supply. Only two conference papers deal with consistency alone. They examine the role of ICT-based solutions in supporting sustainable agriculture (Grunfeld and Houghton 2013, Batchelor et al. 2014), for example, by scaling up the use of organic input with the help of digital platforms to exchange knowledge on organic input production as well as trade those inputs (Grunfeld and Houghton 2013). Hence, research on how ICT can enable a circular economy regarding other resources than energy is scarce.

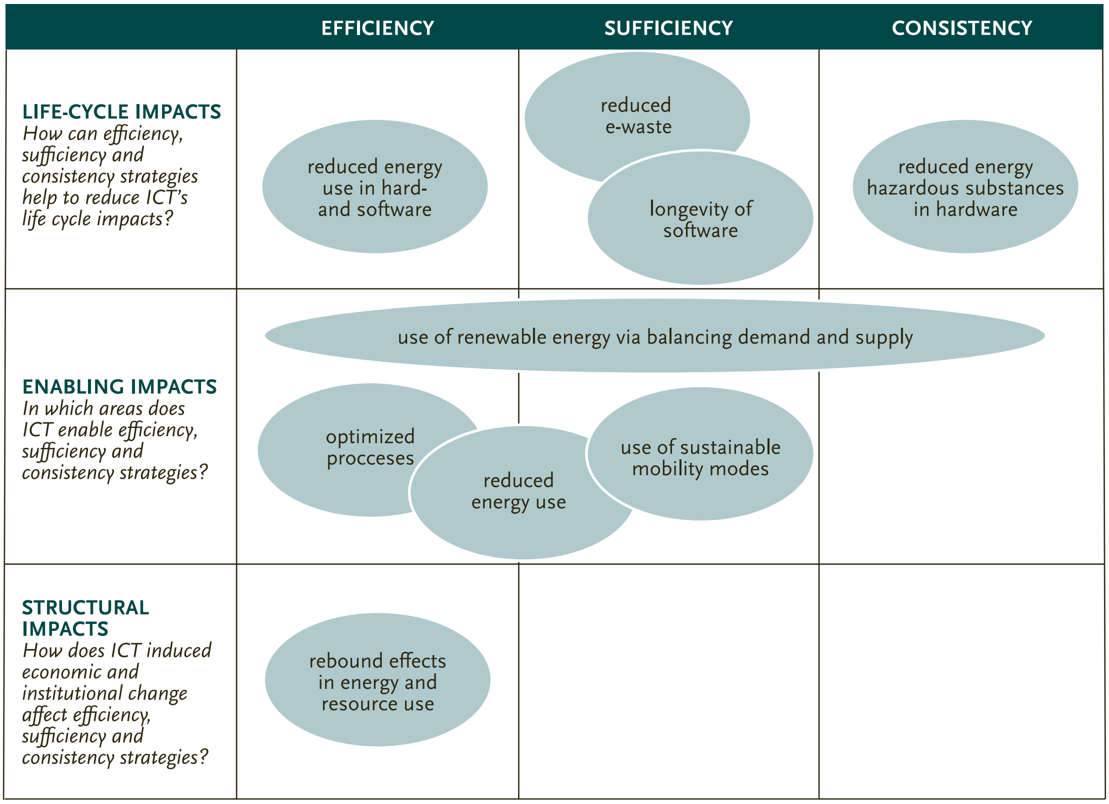

FIGURE 1: Research clusters within *ICT4S* proceedings of the years 2013 to 2019.

Level of ICT's life-cycle effects

Significantly fewer conference papers address the level of *life-cycle effects of ICT (n = 66)*. For 45 conference papers, the focus is again clearly on efficiency aspects, mostly *energy efficiency* (37 conference papers). In several conference papers the energy consumption of software and hardware is considered as a prerequisite to improve energy efficiency. Van Bokhoven and Bloem (2013) and Hintemann and Hinterholzer (2019) for example, deal with the energy consumption of software in data centres, while Philippot et al. (2014) deal with the energy consumption of websites. Hintemann and Fichter (2015), Hintemann and Clausen (2016) and Hintemann and Hinterholzer (2019) address the energy consumption of hardware, with a focus on hardware in data centres.

Several conference papers deal with the carbon footprint related to the energy consumption of the ICT and the entertainment and media sectors (Malmodin et al. 2013, Malmodin and Lundén 2016, Malmodin and Lundén 2018). Other conference papers focus on energy efficiency measures in data centres (Vandromme et al. 2014, Gysel et al. 2013, Romero et al. 2014), on software level (Koçak et al. 2013, Grosskop and Visser 2013, Chinenyeze et al. 2014, Kalaitzoglou et al. 2014) as well as on chip level (Rexha and Lafond 2019). Five conference papers examining the application of insights of ICT life-cycle assessments in practice also address aspects of resource and energy efficiency (Kramers et al. 2015, Schmidt 2016, Lautenschutz et al. 2018, Oyedeji et al. 2019, Condori Fernandez et al. 2019).

Only few conference papers (n = 11) address *sufficiency* on the level of ICT's life-cycle effects. Bookhagen et al. (2013), Picha Edwardsson (2014), Remy and Huang (2014), Joshi and Pargmann (2015), Thomas et al. (2015) and Schneider et al. (2018) address the problem of e-waste. For example, Bookhagen et al. (2013) deal with how to improve the acceptance for recycling programs. Others examine measures to extend the life span of digital devices, such as reducing the number of owned devices (Thomas et al. 2015) and reusing them or designing for modularity (Joshi and Pargmann 2015, Thomas et al. 2015) and attachment (Schneider et al. 2018) as well as longevity (Joshi and Pargmann 2015, Thomas et al. 2015, Remy and Huang 2014). Three conference papers address problems like unnecessary software configurations (Kern et al. 2015), unneeded software parts (Schmidt 2016) or unnecessary stored data (Romero et al. 2014). Kern et al. (2015), for example, propose sufficiency promoting default configurations, such as a reduced image size for mobile versions of websites. Two conference papers also address sufficiency aspects such as design for reusability, maintainability, modifiability (Oyedeji et al. 2019, Condori Fernandez et al. 2019), or user education on sustainability and awareness raising on resource use in relation to sustainable software system design (Oyedeji et al. 2019).

Even fewer conference papers (n = 8) deal with *consistency* on the level of life-cycle effects. Five of them address the problem of hazardous substances (Joshi and Pargmann 2015, Ercan et al. 2016, Schluep et al. 2013, Wendschlag et al. 2014, Picha Edwardsson 2014).

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Level of structural effects of ICT

Only 34 conference papers could be assigned to the *level of structural effect.* 18 were classified to deal with efficiency, only seven address sufficiency, and none address consistency.

Conference papers dealing with *efficiency* aspects are mainly concerned with ICT-induced energy and resource efficiency and related rebound effects (8 out of 18). Pihkola et al. (2018), for example, examine trends related to energy consumption of mobile data transfer and mobile networks in Finland. The findings include that, although the energy efficiency of mobile access networks has significantly improved, the total energy consumption continues to grow due to increasing data usage and new functionalities. Bieser et al. (2019) examine ICT-induced time-rebound effects by looking at how ICT usage changed lifestyles and time use patterns. A further efficiency related topic identified on the structural effect level is an ICT-supported change in economic structures. Two conference papers deal with structural changes induced in the energy sector by implementing a decentralized digital currency (Mihaylov et al. 2016) or a peer-to-peer trading platform (Murkin et al. 2016). Another addresses the problem of increasing unemployment due to automation, the potential of internalizing external costs with the help of cryptocurrency, and the potential positive impact of ICT-based knowledge sharing infrastructures on people's cooperative behaviour (Penzenstadler et al. 2014).

Regarding *sufficiency,* two conference papers address the problem of users' increasing dependency on ICT devices and applications. Bates et al. (2015, p. 300) examine "how digital technologies have been, and continue to be, adopted in domestic practices – and how the growth of interactions with various ecologies of digital technologies can lead to growth in use and energy consumption". One study explores how "Internet disconnection affects our everyday lives and whether such disconnection is even possible in today's society" (Widdicks et al. 2018, p. 384).

Mapping these findings to research clusters – with at least five conference papers qualifying a topic to be considered a cluster – highlights the *ICT4S* research emphasis on enabling and life-cycle effects, and efficiency.

In need of transformative digitalization research

It is our finding that research published in the *ICT4S* conference corpus to a large extent examines how digitalization enables (energy) efficiency as well as how life-cycle impacts of ICT devices and applications can be reduced. At the same time, much less research examines digitalization's potential to advance sufficiency-oriented practices, and questions of how to foster digital sustainability transformations at structural level are only marginally treated.[2]

Based on these findings, we can draw two major conclusions: first, our findings can be used to better understand current public and political discourses on digitalization and sustainability – and the role science in general and the *ICT4S* discourse in particular might be playing in it. And second, our findings suggest changes in science and funding policy in order to address blind spots in existing research.

In the current public and political discourses on digitalization and sustainability, there is substantial hope in the potential contribution of digitalization to advance efficiency improvements in various sectors (mobility, agriculture, energy, etc.) and industries (BMU 2020, see, e.g., CODES 2022, Digitaleurope 2021, EESC 2020, GeSI and Deloitte 2019). The potential impact of digitalization on advancing sufficiency or consistency is much less considered (see, e.g., Ellen Macarthur Foundation 2019). Without overstressing the role for public discourses of science in general and of the specific *ICT4S* conference proceedings in particular, there appears to be a correlation between the key issues in research and the key issues in politics. Is the scientific community partly responsible for the public discourse's one-sided focus on efficiency? Or is it just much simpler to come up with technology solutions than to change social systems and challenge values?

Accordingly, conclusions for funding and science politics can be drawn. There is a deep need to foster research on how digital innovations are embedded in political, economic, and regulatory systems.

While improving efficiencies is a worthwhile strategy, a more balanced approach that covers efficiency, consistency, and sufficiency would be desirable. This holds true, for one, in general, because important sustainability goals such as steep greenhouse gas emissions reductions can best – or even only – be achieved by a smart combination of all three strategies (BUND et al. 2008, chapter 8). And, more particular, because efficiency improvements generate rebound effects that intensify production and induce a more intensive application of digital technologies – which in turn countervails the digital savings potential (Herring 2009, Santarius et al. 2016). Even the most recent IPCC report devotes special attention to sufficiency policies (IPCC 2022). If policy makers are advised to carefully balance efficiency strategies with consistency and sufficiency strategies in a comprehensive policy mix (for a concept for digital sufficiency, see Santarius et al. forthcoming), this should be claimed for research as well: rela-

2 For similar findings in public discourses see Angst and Strauß (2023, in this issue).

tively more research is needed that investigates digitalization's potential for a circular economy and for sufficiency, and more research should pursue a holistic view considering combinations of all three sustainability strategies.

In a similar vein, current policy making regarding digitalization for environmental sustainability has a strong focus on both unleashing enabling effects and reducing life-cycle effects. Take, for instance, the 2021 EU Council decision *Digitalization for the Benefit of the Environment:*[3] most of the policy initiatives suggested focus on digitalization as a leverage for environmental protection, while in the final part initiatives are suggested to make ICT themselves, particularly data centres, more environmentally sound (i. e., green IT). The same holds true for the few policy prescriptions at national level, for example, in Germany and Finland, which also focus on green IT and digital enabling factors (BMU 2020, LVM 2021). Again, this focus of the political and public debate appears to correlate with the state of the scientific debate in the *ICT4S* conference corpus.

While it is important that politics addresses challenges of green IT, it is probably even more important to address the indirect and structural environmental impacts of digitalization on overall production and consumption patterns (Lange and Santarius 2020). If sustainable development requires not only technological and incremental changes but profound social changes, including changes in values, institutions, and practices (see WBGU 2011), then "making digitalization work for sustainability" is far more complex than greening technologies and leveraging optimizations. The big question for both research and politics is how to make digitalization a driving force for deep and society-wide sustainability transformations. Research, at least in the *ICT4S* conference corpus, is so far not well equipped to provide solutions – and maybe research is part of the reason why the political debate is not focused on this question.

Accordingly, conclusions for funding and science politics can be drawn. There is a deep need to foster research on how digital innovations are embedded in political, economic, and regulatory systems. Simply changing technologies to become more efficient might be possible without such insights, but the implementation of comprehensive strategies that combine efficiency, consistency, and sufficiency requires a profound understanding of technology's role and embeddedness in existing socio-economic contexts. In particular, if a change in consumption and production patterns for greater sufficiency is desired, research is needed to more comprehensively understand how to foster technology adoption, use, and acceptability *outside of* and *beyond* existing power structures in order to support new practices. In particular, research is necessary on how certain digital solutions can help disrupt present path dependencies and break up lock-in modes of unsustainable production and consumption. In short, science politics and funding – at EU level, but also at a national level and within the private sector and civil society – should favour research on digitalization that rests on a coherent and transformative combination of all three sustainability strategies.

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3 *www.consilium.europa.eu/en/press/press-releases/2020/12/17/digitalisation-for-the-benefit-of-the-environment-council-approves-conclusions*

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The contribution of data science applications to a green economy

Data science driven applications (e.g., big data and artificial intelligence) can support the transition to a green economy. However, this requires overcoming existing barriers and providing appropriate framework conditions. Based on an analysis of 295 German and US start-ups using data science to create positive environmental impacts, we identify six main obstacles to a greater use of data science for sustainable transformation, and propose six measures that can be used to formulate policy recommendations.

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The contribution of data science applications to a green economy
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Abstract
This paper examines the intersections between the hoped-for shift toward a green economy and data science (various forms of big data analytics and artificial intelligence). It does so through an analysis of data science applications with environmental relevance developed or deployed by German and US start-ups. The majority of the data science applications identified seek to improve the efficiency of existing products and processes, or to provide information. Applications that support more fundamental transformations of existing production and consumption patterns are fewer in number. To increase the sustainability-related impact of data science, it seems necessary to adjust policy framework conditions. Based on our findings, recommendations for action are presented regarding sustainability-related changes of the legal and regulatory framework conditions.

Keywords
artificial intelligence, big data, data science, green economy

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The term green economy was first used on the world stage in 2012 by UN Secretary-General Ban Ki-moon as an umbrella approach that brings together all economic policies relevant to sustainable development. Green economy is thus the guiding principle of an environmentally sustainable economy that combines ecology with social welfare-oriented growth (UNEP 2011).

A major development of the last decade has been the enormous increase in the availability of data across all manner of domains as well as technologies to analyze it. These include artificial intelligence (AI) and "big data" as well as the more standard statistical and descriptive approaches, collectively often referred to as "data science". This "data revolution" is widely perceived to promise significant economic and welfare gains (Manyika et al. 2011). An important question is whether and how data science, as well as digital technologies in general, also support the transition to a green economy. Growing literature on this topic can be divided into several strands. One strand studies the effects of the growth of digital technology on energy and resource use (Lange et al. 2020, Kern et al. 2018, Bordage et al. 2021). Another strand involves discourse analyses of relevant state policies (Kettenburg 2019). Finally, numerous studies catalog the environmental potentials as well as the risks of digitization and data science technologies like AI (Rolnick et al. 2019, Cowls et al. 2021, Vinuesa et al. 2020, WBGU 2019). These studies are mostly based on literature reviews of published scientific work and expert assessments. There has been little empirical research so far on how companies and other actors like state agencies and NGOs are using data science for sustainability purposes. This was a key question we examined as part of our project for the German Environment Agency (UBA) – *Interactions between the process of digitalization and the transition to a green economy* (Gotsch et al. 2022). The following summarizes some conclusions of this larger work, focusing on sustainability-related uses of data science by start-ups.

The transformation toward a green economy is accompanied and supported by new possibilities of digital change (WBGU 2019). Therefore, the influence of data science on the transformation process needs to be examined in more detail. However, >

it must be noted that private-sector activities and research work must always be seen in the context of the underlying political circumstances. Consequently, it is policy makers who set the regulatory framework within which private stakeholders may or may not contribute to the transformation of their behavior and help of new digital opportunities, depending on the incentives.

The green economy

Transition to a green economy means changing the structure of institutions and mechanisms on several levels – macro, sectoral, company, and consumer. In principle, each of the three central sustainability strategies for a transition to a green economy – *efficiency, sufficiency,* and *consistency* – should be taken into account (Meyer 2020, Sühlmann-Faul 2020). The *efficiency strategy* aims at a relative reduction in resource consumption (Kahlenborn et al. 2019). The *sufficiency strategy* means changing existing production and consumption patterns in order to use less energy and raw materials in absolute terms. As a consequence, these behavioral changes then save resources (Heyen et al. 2013). The *consistency strategy* aims at a qualitative transformation of industrial material turnover in which the aggregate consumption level stays the same or even increases without endangering the environment (e. g., by switching to renewable energy sources) (Huber 2000).

The *efficiency strategy* seems to be the most readily compatible with current business models and regimes and could therefore be the easiest to implement. At the same time, the degree to which efficiency gains in themselves transform society and the economy toward a more sustainable one is probably limited. *Efficiency strategies* also carry the greatest risk of merely entrenching existing (unsustainable) structures and leading to rebound effects. Compared to the efficiency strategy, the *sufficiency strategy* promises significantly greater contributions to transformation, especially in the long term. However, the *sufficiency strategy* has a rather low sociocultural potential and it seems questionable whether sufficiency will ever be suitable for the mass market (Kahlenborn et al. 2019). The *consistency strategy* probably offers the greatest contribution to transformation in the long term. However, significant resistance and path dependencies (legal, economic, technological, organizational, and user-related) must first be overcome, which seems unlikely to be successful in all cases for a variety of reasons.

Methodology

To understand the potential and current use of data science for the green economy, we constructed a unique data set of 295 German and US start-ups (226 US and 69 German companies), whose products and services (use cases) rely on data science and who claim to have a positive environmental impact. The data was collected from the *crunchbase.com* database and start-up accelerators, as well as from a detailed manual examination of each company's website.[1]

For each start-up, the professed positive environmental effects of its product/service were identified and categorized by its type of contribution to a green economy transition, as well as the sector or subsector where these effects are manifested. The basic assessment of the plausibility of the start-ups' environmental claims was based on the information provided on the company website and our own expertise and excluded any obviously doubtful cases. The professed environmental effects of each start-up's products/use cases were then coded according to whether they contributed to the *efficiency, sufficiency* or *consistency strategy*. The coding was done independently by three of the authors, with any differences in coding subsequently discussed and resolved.

We gave particular attention to start-ups due to their crucial role as incubators of new technologies and business models (Achleitner et al. 2019). However, as part of the larger project, we also examined use cases adopted by ten German and US companies, seven German and international environmental NGOs, and several European and US state agencies (results reported in Gotsch et al. 2022).

To better understand the potential and constraints of the use of data science in green economies (both by start-ups and by other actors like NGOs, state agencies, and other companies), we conducted 32 semistructured expert interviews with company executives, academics, civil servants, and NGO staffers. All interviewees had spent a minimum number of years in the fields of both data science and environment/sustainability. The questions varied somewhat according to the interviewee's expertise and professional position, but they generally covered the following points: how data science was currently used for sustainability purposes in the interviewee's sector, whether untapped potential existed, which data sources and data accessibility ocurred, and what the interviewee perceived as the main obstacles and limitations to a greater use of data science for environmental and sustainability purposes, including business, technological, regulatory, and market/customer-related obstacles. Conclusions derived from these interviews were then presented and refined at an expert workshop in late 2021.[2]

Key findings regarding start-ups using data science to create positive environmental impacts

This section describes some of the main findings from our analysis of data science start-ups, including the sectoral distribution

1 For further detail on our methodology, see the online supplement: *https://doi.org/10.14512/gaia.32.S1.6.suppl*. In most of the use cases, the company website was the only data scource available.

2 Due to the UBA's interest, the interviews focused on the situation in Germany. We would like to thank all interviewees and workshop participants for their time. The views and analysis presented here solely reflect the authors' personal opinions and should not be attributed to any specific interviewee or workshop participant.

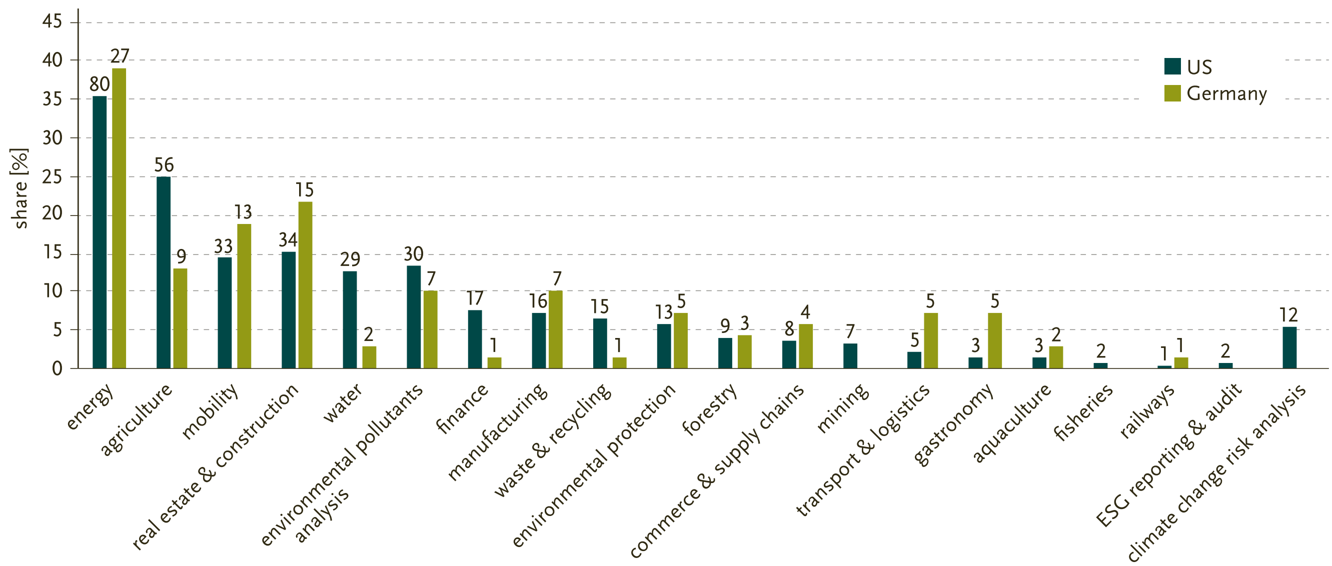

FIGURE 1: Sectoral distribution of data science start-ups in the United States (US) and Germany. Each start-up may be active in multiple sectors simultaneously (figures on the bars stand for the total number of start-ups). ESG: environmental social governance.

of US and German start-ups (figure 1). The figures in percents describe the share of German and American start-ups active in a given sector. Each start-up may be active in multiple sectors simultaneously; the sectors are based on the statistical classification of economic activities in the European Community (NACE).

There are several points which stand out. First, the sectoral distribution in both countries is quite similar. The main sectors in which start-ups are active include energy, agriculture, personal mobility, water industry, pollution monitoring, and real estate[3], followed by a long "tail" of sectors with only a few firms. As discussed in detail in Gotsch et al. (2022), this similarity also extends to the subsector level: in terms of numbers across the sectors, American and German start-ups tend to pursue similar applications and use cases. Typical use cases include realizing energy, water, fertilizer, herbicide/pesticide, and fuel savings; monitoring air and water pollutants and greenhouse gas emissions; optimizing the deployment, operation and maintenance, and grid integration of renewable energy and electric vehicles; and improving public transport. The sectoral focus and use cases of the multinationals examined are similar to those of start-ups (Gotsch et al. 2022).

Second, a corollary of the comparable sectoral distribution is that there seem to be few "blank spots", that is, sectors or use cases dominated far more heavily by firms from one country or the other. At least in the field of developing environmentally oriented data science applications, there is no obvious evidence that German companies lag behind American ones.[4]

Third, however, there are a few sectors where US start-ups are significantly more active: namely, agriculture, water, finance, waste/recycling, and analysis and forecast of climate change risks. The expert interviews indicated mostly sector-specific reasons for these divergences, that is, they do not indicate a more general, systemic weakness in the German innovation system for environmentally oriented data science. For example, different agricultural structures (field and farm sizes, crop types) and differences in the levels of water stress and better water infrastructure mean that the business cases for many data science-based precision agriculture and water management applications may be weaker in Germany than in America. Similarly, much of the practical climate-risk analysis commercialized by start-ups in the US is performed by applied research institutes in Germany that have no direct US equivalent.

We next sought to categorize the products and use cases developed by the start-ups according to the type of contribution they made to a green economy transition in order to draw conclusions about whether they were contributing to *efficiency, sufficiency,* or *consistency strategies*. Inductively, we arrived at five broad classes of products/use cases (figure 2, p. 32). About 55% of start-ups in both countries offer products that promise efficiency improvements within the context of existing modes of production and consumption (e. g., precision agriculture, water, or energy savings). These correspond most clearly to the *efficiency strategy*. A smaller proportion of firms, 32% in Germany and 37% in the US, are developing products that directly implement or fundamentally support new and more sustainable systems (e. g., renewable energy, circular materials economy, organic or urban vertical agriculture, and mobility systems built around public transport, electric vehicles, sharing and walking/cycling). >

3 Many of the firms active in real estate are essentially energy and water services companies focused on realizing efficiency savings in buildings.

4 While we identified more than three times as many American start-ups as German ones, this must be considered in the context of the US economy being more than five times the size of the German one.

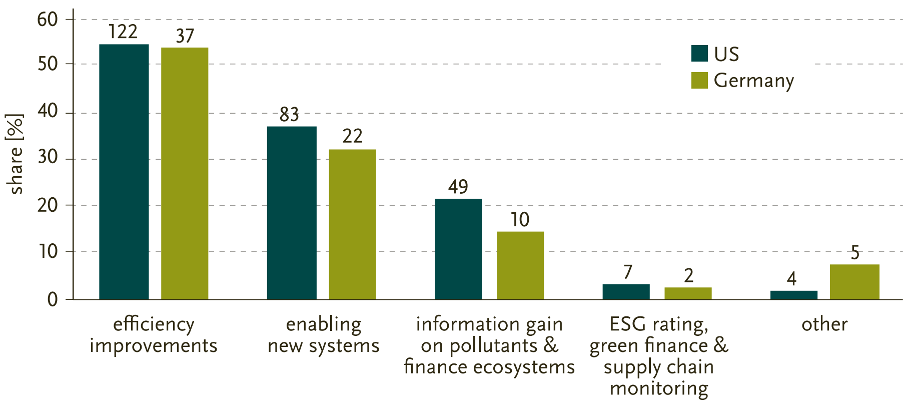

FIGURE 2: Types of use cases pursued by data science start-ups in the United States (US) and Germany. ESG: environmental social governance.

These correspond to the consistency strategy. Importantly, data science start-ups hardly ever try to implement sociotechnical systems such as these in their entirety. Instead, they tend to offer specialist products that support particular aspects of these systems (e.g., automated operation and management for wind turbines with drones and AI). Especially in the energy sector, many companies offer solutions to improve both efficiency and new systems (e.g., energy management software to reduce consumption and improve the grid interaction of self-produced renewable energy).

In addition, 14% (Germany) and 22% (US) of the start-ups offer solutions that mainly provide information (data, analysis) about pollution (e.g., air, water, soil, greenhouse gas), ecosystems (e.g., tree cover, composition of fauna/flora populations), or geophysical processes (e.g., wildfires, climate change). These correspond to either *efficiency* or *consistency strategies,* since high-quality data and analyses on pollution, ecosystems, or climate change are necessary for both. There are also many start-ups in this field that are pursuing both "new systems" and "efficiency" use cases (e.g., a start-up specializing in earth observation data analyses could offer specific products for monitoring methane emissions, identifying optimal sites for solar power, and optimizing fertilizer use in precision agriculture).

Both in Germany and the US, some 3% of start-ups offer products for corporate environmental social governance (ESG) ratings, sustainable finance (i.e., "green" investment ratings and portfolios), and supply chain monitoring. These use cases are also arguably in line with both the *efficiency* and *consistency strategies.* At present, these products mainly promote efficiency (output per unit of pollution/resource consumption). However, in the longer term, the information they generate and the incentives they help to create for corporations may very well promote the qualitative change in production and financial systems implied by the *consistency strategy.*

Finally, 2% (US) and 7% (Germany) of start-ups offer various kinds of "other" products (e.g., apps to help guide personal consumption by providing information on the carbon footprints of products or analytics systems for corporate users to help prevent industrial accidents). Most of these do not clearly correspond to any of the three strategies.

In summary, we found that the largest number of start-ups in both countries offer solutions that mainly support *efficiency strategies,*[5] while about a third have products that directly support *consistency strategies.* Around 20% have products that would support either strategy. Finally, none of the start-ups seem to develop products that clearly correspond to *sufficiency strategies.* Arguably, this should not come as a surprise: efficiency use cases are highly consistent with existing business logic (the cost reduction imperative) and should therefore be relatively easy to justify to potential clients. AI and big data are also well-suited to sieving through huge reams of data to find efficiency gains. Conversely, it seems that the absolute, not just relative, reduction in consumption that *sufficiency strategies* require is most at odds with conventional business logic and the imperative of companies, including start-ups, to consistently increase their revenue. Therefore, the fact that none of the start-ups appears to be developing products in line with this strategy is not unexpected.

Finally, the broad-based systems transformation that is implicit in the idea of *consistency strategies* entails a multitude of complex technological, organizational, and business challenges, and it should thus create large numbers of new business opportunities. It is therefore not surprising that we see significant numbers of start-ups developing such products. At the same time, products that support genuinely new systems can be particularly challenging, both technologically and in business terms, since the systems themselves are still in the process of emerging. Therefore, it is perhaps not surprising that the number of companies in this field is somewhat smaller than those pursuing the more straightforward efficiency cases.

Results of the study

In order to identify the biggest obstacles to the greater use of data science for a green economy, we systematized the various obstacles that emerged from our analysis of the start-up data set and the expert interviews, according to whether they related to business, technological, regulatory, or market/customer factors. We validated these findings in a workshop with selected experts, in which we presented the different obstacles identified in our interviews and analyses, and asked the experts to assess and comment on the relevance and prevalence of these obstacles.

5 For similar findings in the research community see Santarius and Wagner (2023, in this issue).

According to our results, the biggest obstacles in Germany to the greater use of data science for the green economy, both by start-ups and other actors (e.g., small and medium sized enterprises, non-governmental organizations, and state agencies), lie in the areas of 1. data availability and data quality, 2. data access, 3. data infrastructures, 4. lack of understanding of the possibilities and limitations of digital technologies, 5. regulatory hurdles, and 6. cost-ineffectiveness and insufficient uptake.

1 ***Data availability and data quality.*** The necessary data are not available. The reasons are often of a general nature (e.g., a lack of economic incentives to invest time in creating and processing data). The creation of good digital data sets not only requires appropriate technical equipment (e.g., sensors) but also considerable domain knowledge.

2 ***Data access.*** Even if data are available in a digital format, they are not always accessible. For private data, there are concerns about leaking trade secrets. For publicly available data, awareness of open data has grown but is not yet universally applied. It is still difficult to find out which government agency (and which department within that agency) actually collects certain data, where these data are located, and who to contact to obtain them.

3 ***Data infrastructures.*** Data science requires powerful IT infrastructures to merge, store, and process data. Start-ups, in particular, may struggle to access the necessary infrastructure and equipment. Use cases such as the circular economy, which require extensive data sharing across companies and sectors, present a particular challenge. Often, the infrastructure required to enable such data sharing does not exist. Building a suitable infrastructure often requires not only investments in hardware but also in personnel (jobs, training, etc.), as well as extensive interorganizational coordination.

4 ***Lack of understanding of the possibilities and limitations of digital technologies.*** Non-governmental organizations and small and medium sized enterprises usually do not have the financial resources that would enable them to build strong data science departments. Specialists and executives in companies, municipalities, and NGOs often lack a sound understanding of the possible uses and limits of the technology in their domains. Conversely, data scientists and AI experts in universities and research institutes often lack a deeper understanding of the specific problems and framework conditions of the respective domains.

5 ***Regulatory hurdles.*** In most of the domains relevant to a green economy, there are complex, domain-specific regulatory frameworks with numerous detailed regulations. In addition, most green economy-relevant domains belong to the area of critical infrastructure with high security requirements, where regulatory adjustments can only be made with caution. Specific difficulties lie mostly in the details of individual domain-specific regulations, which create barriers to data access and use.

6 ***Cost-ineffectiveness and insufficient uptake.*** Without a common vision for the future that provides a framework, developments will take place in a variety of directions. This will lead to uncertainty among private-sector actors with regard to investments. Environmental potential can only be harnessed within a framework where the boundaries and goals are clear.

Overall, it is apparent that only a few of the obstacles mentioned are directly related to environmental regulation, which means that the majority of obstacles cannot be solved by the activities of the environment ministry or its subordinate authorities alone. Therefore, solutions can probably only be found in coordination with all the respective political actors and stakeholder groups involved.

Conclusion and policy recommendations

The data science applications analyzed revealed multiple examples of applications for a green economy. However, most of these applications aim to improve the efficiency of existing production paradigms or to provide additional information. This shows that it is crucial to actively refocus the purpose of digital transformation and develop shared visions, values, and goals for sustainable development in the digital age.

The findings of this paper can be used to formulate policy recommendations that can provide a framework for overcoming barriers and integrating digital technologies on the path to a green economy. They will be discussed in ongoing policy processes and in the multistakeholder group *Coalition for Digital Environmental Sustainability (CODES)* (2022), a global alliance of governments, businesses, and civil society.[6]

According to the authors of this paper, the following six measures can help overcome obstacles and support a greater use of data science for green transformation.

1 With regard to ***data availability and data quality,*** data experts perts and domain actors should be consulted to assess whether the publicly funded creation of high-quality reference data sets makes sense. There should be a clear prioritization of the domains and application clusters for which these reference data sets would be created. Public research funding could also provide more support for the creation and publication of high-quality data sets.

2 ***Improved access to*** data could be created through economic incentives, which would make data sharing more attractive to private actors. The development of technical solutions that en- >

6 *www.sparkblue.org/CODES*

able data processing under high-security guarantees and without access to nonanonymized data should also be supported. The implementation of open data in the public sector needs to be further strengthened in order to improve the ability to find existing data. The German National Research Data Infrastructure[7] has begun to close these gaps, but there is still a need for further action.

3 In order to create the necessary ***data infrastructure,*** public funding could be provided for modern data technology for start-ups or NGOs. The establishment of government institutions (which has already begun, for example, in Germany with the National Environmental Information Centre,[8] the Artificial Intelligence Laboratory for Sustainability Solutions,[9] or the National Center for Monitoring Biodiversity[10]) can create new data infrastructures for sustainable solutions. This also strengthens environmental governance through digital tools. In order to use the emerging transformation dynamics through digitalization for the ecological transformation ("double transformation"), environmental governance needs new structures, processes, and competencies to effectively use and shape the new technologies.

4 There are already several initiatives to promote a ***better understanding of the possibilities and limits of digital technologies.*** These initiatives (such as the community *Sustainable Digitalization*[11] of the German Federal Environment Ministry or the *Bits & Bäume*[12] initiative) need to be strengthened further, but beyond that, there should be targeted research into what the explicit hurdles to networking are and how they can be best addressed. In order to raise awareness about the possibilities of digital technologies, workshops could be offered (e.g., with foreign stakeholders who have been using these technologies for a long time and on a larger scale, as well as with application-oriented scientists). These workshops could also be organized for small- and medium-sized companies in selected domains. Within the framework of government research funding for sustainable data science applications, there should be more calls for applied research aimed at cooperation and consortia building between start-ups, research institutions, and NGOs in order to institutionalize the exchange. A successful example of this can be seen in the *AI Lighthouse Projects for the Environment, Climate, Nature and Resources* intiative, which is funded by the German Federal Environment Ministry.[13]

5 In order to overcome existing ***regulatory hurdles,*** the use of regulatory sandboxes and living labs should be further promoted – in which existing rules and regulations are temporarily suspended and if appropriate, regulations are subsequently adjusted in light of the knowledge gained. In general, future regulatory projects should, if possible, be provided with exception and experimentation clauses in order to support the nonbureaucratic implementation of sandboxes and living labs. Within this framework, controlled access to real, critical, or personalized data could then be enabled in order to identify which precise aspects have to be regulated. In future revisions of data protection law, public interest in increased data use for the transition to a green economy should be given greater consideration. For example, stronger enabling structures should be enshrined in the law and public interest in data use should be more institutionally anchored. This should be considered part of the upcoming implementation of legislative initiatives of the European Union on an international level, for example, the *Digital Services Act* (Regulation [EU] 2022/2065) or the *Digital Markets Act* (Regulation [EU] 2022/1925).

6 In order to provide an ***appropriate framework for real transformation,*** the economic viability and acceptance of sustainable digital applications in particular would have to be strengthened. This may require a coordinated government intervention in the form of a framework for a vision of the future. A good example of this is the *Natural.Digital.Sustainable* action plan of the German Federal Ministry of Education and Research.[14] This intervention should be a coordinated, concerted mix of financial incentives, subsidies, sensible regulation, and, if necessary, an expansion of transparency, testing, and due diligence obligations and bans. For example, a mission-oriented innovation policy seems suitable for this purpose, as it could provide and coordinate the necessary framework.

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Digital circular ecosystems: A data governance approach

Strategic product data management fosters circular ecosystems that reduce carbon emissions and resource consumption. To this end, legal frameworks are needed to set standards for systematic product transparency and interoperable tracking of materials. Analyzing the EU's Digital Product Passport (DPP), we propose the creation of publicly coordinated product data platforms to complement DPPs.

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Digital circular ecosystems: A data governance approach
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Abstract
The growing research interest in digital product passports (DPP) and circular economy platforms portends an ecological economic transformation that will require improved strategic product data governance. Using the literature, we explore the technical and policy frameworks required by data-based policy instruments for digital circular ecosystems (e.g., DPPs). We analyze five empirical product life cycle cases to better understand how the strategic governance of product-related data can connect materials and product flows to shape new collaborative circular ecosystems. For this purpose, we provide new governance proposals for modifying European DPPs to enable the systematic tracking of materials.

Keywords
circular economy, data governance, platform, regulation, sustainability

Over the past decade, EU regulators have recognized data as a strategic resource. Hence, we now have a European data law (Streinz 2021), which addresses the strategic role of information. Policy instruments (e.g., mandatory data-sharing and interoperability obligations) are developed to tackle the asymmetric information power of "Big Tech" (Brown 2020). Unfortunately, scant public attention has been paid to data regulations in the context of sustainability transformations. Hence, the European Commission is deploying data governance policies to stimulate the desired ecological transformation. The Digital Product Passport (DPP) is a relevant example. The general idea is that manufacturers should make important product-related data digitally available so that stakeholders can reuse the knowledge and materials involved (Adisorn et al. 2021).

The circular economy approach also highlights the role of data governance in the ecological transformation of the economy. Circular economy scholars tend to view it as a policy tool for supporting circular ecosystems, monitoring ecological costs, and increasing material efficiency throughout product life cycles (Berg and Wilts 2019, Hedberg and Šipka 2021, Kristoffersen et al. 2021). However, there is no current agreement on the specifics of the product data required or on how they should be collected and curated. Instead, 76 projects are under way to provide competing EU DPP formats (Jansen et al. 2022, p. 12).

This paper explores the data governance requirements of a circular economy and specifies the technical and policy requirements for product data sharing. We draw on recent literature in the field of information systems and data-based collaboration (Lis and Otto 2020, de Prieëlle et al. 2022) to support our central argument that policy interventions (e.g., DPPs) must be accompanied by comprehensive data governance policies (Piétron et al. 2022). That is, precise rules for generating, storing, accessing, and using product-related information are needed to support circular ecosystems and ultimately empower stakeholders to close material cycles and promote longer product lifetimes.

We proceed with this task in three steps. First, we lay out the theoretical implications of digital circular ecosystems and distinguish centralized digital platforms from decentralized DPPs. Second, we develop a data governance analysis framework and apply it to five exemplary cases of digital circular ecosystems.

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Third, we analyze the data governance structure of the EU's DPP proposal and examine the technical and policy gaps that need to be filled to implement a data-based collaboration framework that will support circular ecosystems.

Concept of digital circular ecosystems

In recent years, the circular economy paradigm has gained popularity among policymakers, business leaders, and researchers as a pillar of sustainable society. In contrast to the orthodox "take – make – dispose" logic of value creation and destruction, a circular economy is a system in which value is created using existing products and materials across multiple-use cycles (Blomsma and Brennan 2017, Hofmann 2019). The assumption is that a circular economy will ease the anthropogenic pressure on nature by closing material cycles, extending product lifetimes, and dematerializing value propositions.

The concept of circular "ecosystems" is essential to understanding and pursuing sustainable production and consumption modes (Hofmann and Jaeger-Erben 2020). It is an essential characteristic of ecosystems that they produce system-level outcomes that are greater than the individual contributions of the constituent parts (Aarikka-Stenroos et al. 2021). This approach captures the configurations of actors, technologies, and institutions that cooperate through loosely coupled interdependencies and coevolutionary patterns (Thomas and Autio 2020). Actors from different industries interact at all five stages of the product life cycle (Hansen and Revellio 2020):

- ***Design.*** Product designers develop durable products whose modular designs permit low-emission, resource-efficient production and use, and easy repair and recycling.
- ***Production.*** Manufacturers ensure low-emission production of modular, durable, repairable, and upgradable products, by using renewable energy and recycled materials.
- ***Usage.*** Service providers enable collective usage and shared consumption of product-as-a-service systems to increase efficiency of products.
- ***Second life.*** Repairers and remanufacturers extend product life through maintenance and repair, refurbishment and resale, and reassembly with new components as required.
- ***Recycling.*** Recycling industries track and separate material flows to avoid waste and generate secondary raw materials.

Various factors hinder the institutional shift to a circular economy, for example lack of economic incentives, low raw material prices, technical path dependencies, and rapid innovation cycles. However, for inter-organizational cooperation in a circular ecosystem, communication and information deficits are major obstacles that lead to uncertainty and unstable relationships. As Berg and Wilts (2019, p. 4) stated, "the circular economy's implementation is primarily a problem of information". Echoing the information-oriented explanations of social structures from institutional economics (Williamson 1981) and economic sociology (Beckert 2009, pp. 259 ff.), scholars have identified informational problems that hamper the transformation to a circular economy (Berg and Wilts 2019, Hedberg and Šipka 2021, Jäger-Roschko and Petersen 2022). First, deficient information flows for secondary materials and used products (e. g., quantity, quality, and value) lead to high search costs. Second, the externalization of the ecological costs of new products leads to unjustified price disadvantages for used products and secondary materials. Third, information deficits prevent repair, remanufacturing, and recycling, often due to intellectual property rights. Fourth, the shared consumption of goods and services is hampered by a lack of trust and connectivity.

Consequently, various actors seek to employ the latest information and communication technologies to create *digital circular ecosystems* that may be centralized or decentralized. On one hand, existing circular ecosystems tend to be orchestrated by a central actor functioning as the information broker to reduce transaction costs (Paquin and Howard-Grenville 2013). In recent years, digital platform technologies have been employed in many circular ecosystems to establish centralized multi-sided online marketplaces (Blackburn et al. forthcoming). We conceptualize these as *circular ecosystem platforms* as their algorithmic infrastructures centralize information flows to facilitate the reuse of products and materials, thus reducing the overall consumption of resources. Examples include platforms for exchanging used products, components, and secondary raw materials (e. g., eBay or Cirplus), building collaborative open-source communities (e. g., GitHub), sharing product repairing information (e. g., iFixit), and accessing shared services and infrastructures (e. g., mobility-as-a-service platforms).

DPPs, on the other hand, can be regarded as components of a decentralized data infrastructure that enables the exchange of product-related data without a central information broker. As envisaged by the European Commission (EC 2022, p. 9), a DPP should "electronically register, process, and share product-related information amongst supply chain businesses, authorities and consumers". Hence, DPPs require a unified and harmonized data standard that allows the functional interoperability of heterogeneous information systems for sharing product data among various companies and sectors (Brown 2020).

Data governance for circular ecosystems

Technically, digital circular ecosystems – whether centralized or decentralized – must perform two basic functions. First, they must provide reliable information about the characteristics, quality, and components of products. Second, they must facilitate standardized data flows among independent actors to maximize value generation. Both functions are addressed by the research field of data governance (Khatri and Brown 2010). Essentially, data governance encompasses decision-making rights and rules about the collection, storage, processing, and sharing of data within and between organizations (Abraham et al. 2019). Accord- >

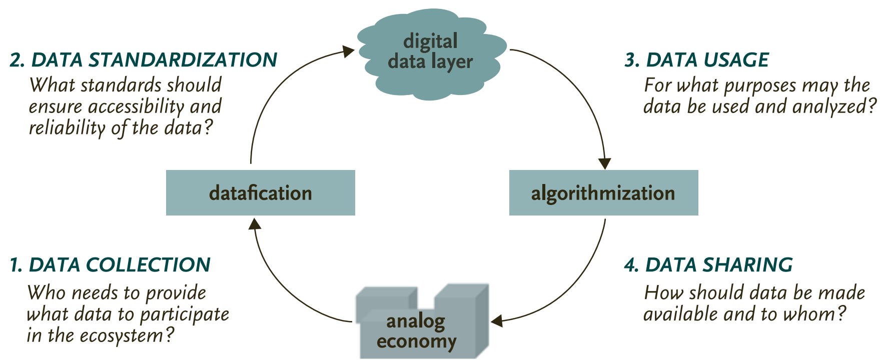

FIGURE 1: Data value chain: data collection generally represents the "beginning" of strategic data governance, with data sharing in the fourth stage, situated closer to the end of data-based value creation. Although this analytical chronology offers practical advantages, data governance is, in fact, recursive.

ingly, effective collaboration and risk mitigation requires clear rules about which stakeholder provides what data, how the data will be processed, and who will have access (de Prieëlle et al. 2020). To this end, the "data value chain" (Curry 2016) is a common analytical framework for multi-stakeholder information system governance. For circular ecosystem data governance we propose the following steps: *data collection, standardization, usage,* and *sharing* (figure 1).

In the following subsections, we apply our data governance perspective to five examples. We analyze digital circular ecosystems along the product life cycle, paying particular attention to governance mechanisms that specify how data are collected, standardized, analyzed, and shared. The cases were selected for their ability to demonstrate the potential of digital circular ecosystems based on product data from all five product life cycle stages. Owing to the great heterogeneity of projects from different sectors and groups of actors, their data management commonalities can be analyzed in more detail. Here, we employed a qualitative analysis of strategy papers, policy documents, and selected academic and think-tank studies.

Design: Three-dimensional computer-assisted design modeling of replacement parts to prolong product lifetime

The EU *FIWARE-enabled Service for Spare Parts Logistics in 3D Printing Digital Supply Chains (FIL3D)* project has demonstrated how a circular ecosystem can employ data from the product design phase (González-Varona et al. 2020). It focuses on manufacturers' three-dimensional (3D) computer-assisted design (CAD) datasets, which provide information about materials, tolerances, colors, and production specifications. CAD models serve as templates for 3D printing (i. e., additive manufacturing). Additive manufacturing can thus be used to repair broken producs and extend their life by producing spare parts on demand (González-Varona et al. 2020, p. 12). Using CAD data from a producer, consumers can generate replacement parts printed at a local 3D printing hub to be installed at a repair shop. The *FIL3D* project implements a digital platform to gather CAD data from manufacturers, offer them to consumers, and handle payments. To protect intellectual property rights, data access is limited to certified printers who forward the printed part to the consumer (González-Varona et al. 2020, p. 8).

Production: Life cycle inventory data make ecological costs transparent

Life cycle inventory (LCI) data can be used to assess the amount of greenhouse gas emissions during each phase of the product life cycle – from resource extraction to disposal (Suh and Huppes 2005). In the *Catena-X* business-to-business network, German manufacturers and software companies build life cycle inventory data exchange infrastructures to improve the ecological cost transparency of precursors (Capgemini 2021). Each company along the value chain is required to estimate its carbon dioxide equivalents per unit, add theirs to those of its suppliers, and pass the aggregated figures on to the next company in the chain. Given that car manufacturing, for example, involves up to 10,000 individual parts from more than 1,000 suppliers, an automated solution is needed. The German software company SAP has developed a new application to connect the enterprise resource planning (ERP) systems of companies along value chains to automatically monitor carbon dioxide emissions. Doing so provides comprehensive footprint calculations that reflect the actual environmental costs of (pre-)products, which can be used to monitor the environmental performance of companies (Reichel and Seeberg 2011).

Usage: Product status data promote sharing and maintenance

Status data tracking of product location, condition, and availability during the usage phase can enable shared consumption, thus increasing material efficiency as exemplified by sharing platforms (Konietzko et al. 2019). However, most sharing platforms lack interoperability, which impedes easy access and connected offerings. In 2018, the Finnish government introduced a data regulation mandating private and public mobility service providers to ensure the interoperable exchange of vehicle status and booking data. Following the principle of interoperability, a ticket for Mobility Provider B can be purchased via Provider A (Pursiainen 2019). Thus, the government aims to increase the accessibility and utility of intermodal (i. e., cross-company) shared mobility services. A similar capability is needed in the field of product maintenance to realize the full potential of a decentralized data-based maintenance ecosystem that includes distributed third-party repairers and remanufacturers (Bressanelli et al. 2018).

TABLE 1: Data governance analysis of five digital circular ecosystems along the product life cycle.

	DATA COLLECTION	DATA STANDARDIZATION	DATA USAGE	DATA SHARING
DESIGN	Producers create *digital three-dimensional (3D) computer-assisted design (CAD) models* of parts during product development.	Intermediaries provide different CAD data standards to enable broad applications that remain independent of suppliers.	Users access 3D model data to print parts with a local 3D printer.	Producers share 3D models via trusted intermediaries that protect intellectual property rights.
PRODUCTION	Producers create *life cycle inventory (LCI) data* for products to track material inputs and ecological footprint.	Companies agree on basic LCI standards to ensure functionality and comparability, software companies agree on common data formats for exchanging LCI data.	Producers and regulators use aggregated LCI data of products to optimize control of ecological performance.	Producers share LCI data via business software.
USAGE	Products generate *status data* about their location, condition, availability, energy consumption, and emissions.	Individual service companies develop data standards to improve the interoperability of shared services and comprehensibility of defective products.	Users easily access shared products, monitor product quality, and profit from an open repair ecosystem.	The sharing of product status data creates an integrated product service system accessible by consumers and repairers.
SECOND LIFE	Producers provide *repair and maintenance information (RMI)* for products.	Individual service companies develop data standards to enhance repairability.	Repairers use RMI data to facilitate product recovery and extend product life.	Producers share RMI data to facilitate product recovery and extend product life.
RECYCLING	Producers create *bill of material (BOM)* data declaring recyclable materials and components.	Individual service companies develop data standards to improve reusability and recyclability.	Recyclers use BOM data to disassemble complex products and facilitate collaborative resource recovery.	Producers share BOM data with recyclers and online marketplaces for secondary raw material.

Second life: Repair and maintenance information data extend life cycles

Repairing complex products such as cars or computers requires extensive knowledge of design and functionality as well as manufacturer-specific error codes. The provision and sharing of repair and maintenance information (RMI) are expected to open up a market for independent (local) repairers, creating a positive environmental impact by extending product life. The EU's vehicle emissions regulation of 2007 (Regulation EC 715/2007) obliges car manufacturers to grant independent repairers unrestricted access to repair and maintenance information data. Article 6 of the *Regulation EC 715/2007* states in general terms that repair and maintenance information data should be made available "through websites using a standardised format [...] and in a manner which is non-discriminatory compared to the provision given or access granted to authorized dealers and repairers". An evaluation by the European Commission in 2016 concluded that this regulation was partially successful. However, owing to the vagueness of specifications for data standardization and provision, car manufacturers tended to make repair and maintenance information data available only to a small group of authorized repairers or to share incompatible formats that prevented third-party repair (EC 2016, p. 9).

Recycling: Bill of materials data facilitate the recovery of raw materials

When a product reaches its end of life and is unrepairable, information about its composition, toxicity, and recycling potential can greatly simplify its recovery and disposal. An example is found in the construction sector, where the Dutch Madaster company provides a digital infrastructure for material passports to track and segregate reusable building materials. For each building, Madaster generates bill of materials (BOM) data that include quantities, chemical compositions, and features of each element to facilitate separation and sorting for later reuse (Burnley 2007). These passports are stored on a central digital platform, allowing users to perform data operations, such as calculating, and sharing. Hence, users can publish product data in online marketplaces to enable collection directly from the site.

From these five examples, we can identify four key commonalities of working heterogeneous data governance models: 1. they help generate or collect specific datasets containing specific product-related data, 2. they employ standardized data formats to ensure interoperability and broad use of the data, 3. they specify the communication channels used to share product data, and 4. they legitimize product data dissemination with the aim of recovering or reusing materials. These results are summarized in table 1. >

Data governance as a policy instrument

The academic discussion on DPPs has only just begun, and many competing standardization processes are in development (Adisorn et al. 2021, p. 2). Hence, many questions about DPP design and implementation remain unresolved. This is reflected in the EU's *Ecodesign for Sustainable Products Regulation (ESPR)* proposal (EC 2022),[1] which explicitly empowers the European Commission to adopt further delegated acts (EC 2022, Article 4) and encourage industry-led initiatives (EC 2022, Article 18) to complement regulation. In the following subsections, we analyze the EU's DPP proposal from a data governance perspective and derive basic technical and political insights from the five case studies discussed above.

Mandatory data sharing

The EU aims to establish "rules for setting requirements on mandatory [...] disclosure of information to market actors along value chains" (EC 2020, p. 2). In particular, Article 7 of the *ESPR* (EC 2022) specifies what data producers are required to share, including information on performance, disassembly, recycling, disposal, repair, and maintenance. Only if these data are provided in a DPP can the product be placed in the European market (EC 2022, Article 8). However, the mandatory provision of data on materials is limited to substances of concern, which limits many applications of the DPP. Moreover, there is a general lack of clarity about the scope and quality of the required datasets, which leads to more confusion. Given that companies generally seek to keep their data private in order to exclusively leverage the value of the data (Martens 2018, p. 11), further clarification on mandatory data sharing from the European Commission is needed (on data access and sharing see also Gotsch et al. 2023, in this issue).

Data standardization

In Article 9 of the *ESPR* (EC 2022), the European Commission requires that DPPs "shall be based on open standards, developed with an inter-operable format". This interoperability requirement is vital to processing DPPs at scale using software from different producers. However, the *ESPR* does not specify sectoral data standards with harmonized technical vocabularies for data formats and collection methods. This dilemma is similar to the interoperability obligation of the 2018 *Finnish Transport Act,* in which market-based product data standardization proved difficult to apply to a competitive multi-stakeholder market environment. As Tirole (2020, p. 16) stated, to eliminate power asymmetries in standardization processes and include the interests of small businesses and non-governmental organizations, standardization processes must be coordinated by governments or neutral nonprofit bodies.

Data accessibility and protection

The draft *ESPR* currently proposes making product data accessible through a "data carrier" attached to the product, which would serve as a link between the product and the data stored online (EC 2022, Article 9). Data carriers are also to be made accessible through retailers (EC 2022, Article 9) and a central registry established by the European Commission that includes product and data carrier identification (EC 2022, Article 12). However, DPP product data must still be stored by manufacturers (EC 2022, Article 10). This decentralized approach may pose difficulties when seeking access to large volumes of product data. For example, the 2007 vehicle emissions regulation mandated automated product comparisons but was hampered by inconsistent online data provisioning (EC 2016, p. 9). As most successful digital circular ecosystems are based on centralized platforms, regulators should consider complementing DPPs with product data platforms, which are comparable to the *European Product Database for Energy Labeling (EPREL)* and the *Substances of Concern in the Products (SCIP) Database* of the European Chemicals Agency. Moreover, a centralized platform could act as a trusted intermediary to validate data and protect the intellectual property rights associated with sensitive product-related datasets with varying levels of openness and differentiated "data access regimes" (Martens 2018).

Conclusion

In this paper, we argued that the strategic governance of product data is key to designing circular ecosystems with low carbon emissions and minimizing resource waste. The more digital information that is made available on the design, ecological footprint, accessibility, repairability, and recyclability of products, the faster we achieve circular ecosystems. Based on an analysis of five empirical product life cycle cases, we illustrated a broad variety of data governance approaches and focused on their commonalities. Applying a data governance perspective to the EU's DPP proposal, we hold that the ambiguous technical specifications on data collection and data standards and the lack of comprehensive material tracking guidance may cause high coordination costs that will impede circular ecosystems. Therefore, we propose the creation of publicly coordinated product data platforms that complement DPPs by protecting intellectual property rights and improving data accessibility.

However, this approach has limitations. First, an economic transformation depends on various factors, such as economic incentives and political regulation; hence, the availability of data alone is probably insufficient (O'Rourke and Ringer 2015). Second, the digitization of product data is expected to increase the demand for new technologies and cloud services, possibly

1 For an overview on the *Sustainable Products Initiative* see *https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12567-Sustainable-products-initiative_en.*

leading to overall increases in energy and resource consumption (Lange et al. 2020). Therefore, the growing ecological footprint of information and communication technologies must be accounted for and balanced against the opportunities offered by product data governance.

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Monitoring the *Sustainable Development Goals* in cities: Potentials and pitfalls of using smart city data

Smart city strategies highlight the potential to generate new type of data through new technology, for example crowdsourced data. Based on an empirical study, we show the potentials and limits of using new data for monitoring urban sustainability and especially the Sustainable Development Goals.

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Monitoring the *Sustainable Development Goals* in cities: Potentials and pitfalls of using smart city data
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Abstract
The latest debate on smart cities and sustainability is underpinned by the United Nations' *2030 Agenda* and their accompanying *Sustainable Development Goals (SDGs)*, which place urban data and monitoring systems at the forefront. Therefore, there is a strong need to assess the data-driven capabilities that will help achieve the *SDGs*. To fill the capability gaps between existing tools and *SDG* indicators, new smart city data sources are now available. However, scant indicators and assessment criteria have been empirically validated. This paper identifies some of the challenges alongside the potential of using new local data in urban monitoring systems. A case study of an *SDG* monitoring platform implementation in a district of Berlin is examined, and the results show that the use of locale-specific, and unofficial data not only improves data availability, but it also encourages local public participation. Based on our empirical findings, we determine that the incorporation of new data for urban sustainability monitoring should be treated as a complex social process.

Keywords
indicators, smart cities, Sustainable Development Goals, urban data, urban development

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Since the early 2000s, cities worldwide have been developing so-called "smart city" strategies that have attracted considerable attention from urban researchers (Jong et al. 2015). Despite the abundant literature on the many facets of smart city constructs, a concise definition is lacking, and the specific characteristics remain ambiguous (Miller et al. 2021). Early smart city models were developed and/or supported by large technology companies that provided glossy images of hyper-modern cityscapes but neglected realistic social and environmental considerations. Notable urban studies have criticized negative aspects of these corporate-driven smart cities as lacking democratic legitimacy (Engelbert et al. 2022) or being built upon neoliberal urban agendas (Glasmeier and Christopherson 2015). In recent years, smart city strategies have diversified with the increasing complexity of digitalization in terms of its actors, technologies, and objectives. These approaches range from private projects built from scratch, such as Songdo in South Korea, to commons-based, civil society-driven approaches, such as Barcelona en Comú (Charnock et al. 2021). There is now a plethora of smart city constructs, making realistic ideation extremely difficult. Chang et al. (2021) postulated the need to provincialize smart cities: smart cities now incorporate diverse landscapes of smart and "ordinary" locations that are loosely connected through the use of information technologies, such as big data, location-independent digital data flows, and networked technologies, as well as experimental approaches to applying these technologies (Caprotti et al. 2022). An important crosscutting issue for all approaches is the role of the data. Often, smart cities are envisioned to be constructed upon the emergence, flow, visualization, and commercialization of data (i.e., data-driven urbanism; Kitchin et al. 2018).

Questions of "smartness" and sustainability have also emerged in terms of a juxtaposed desire for smart cities and the vital need for global sustainability (Fromhold-Eisebith et al. 2019). Thus, a close examination of specific smart city policies and their potential impacts on the various dimensions of sustainability is needed. Notably, recent research has highlighted the impact of digital smart grids and smart meters on the promotion of renewable >

energy and the potential of shared mobility in order to foster modes of transport, which depend less on individual car-ownership (Lange and Santarius 2018). However, other authors have identified the development of smart cities as the cause of increased energy consumption and the overuse of raw materials (David and Koch 2019). There is also a risk of stakeholder disengagement with top-down implementation of smart cities (Sontiwanich et al. 2022).

Meanwhile, the United Nations' *2030 Agenda* and the accompanying *Sustainable Development Goals (SDGs)* have generated new debates on smart cities and their sustainability, and urban data collection and monitoring capabilities are central to the issues, and increased government accountability is expected to become a result (Bowen et al. 2017). From this debate, a new brand of sustainability science has begun identifying and evaluating new urban data sources, such as those used in smart city approaches, that can be used to monitor urban sustainability. Kharrazi et al. (2016) argued that urban big data (e.g., sensor data emerging from Internet of Things [IoT] devices), individual- and household-level survey data, geospatial analytics, citizen science, and social media sources can be used to fill the gaps in existing *SDG* data collection and analysis tools. Similarly, MacFeely (2019) discussed the potential of big data cultivated from web-scraping, satellite imagery, and smart meters, and Creutzig et al. (2019) identified the potential to facilitate urban climate solutions through the harmonization of data collection, machine learning, big data approaches and the application of machine learning-based textual analysis of qualitative data. Focusing on social-media data, Ilieva and McPhearson (2018) discussed the specific attributes of social-media data (e.g., geo-tagged Twitter posts) and highlighted their utility for urban sustainability. Fritz et al. (2019) and Fraisl et al. (2020) took issue with the fact that citizen-generated data have so far been largely ignored in *SDG* data collection solutions, despite their obvious advantages, such as being inexpensive and timely.

Although the promise of these data, which we hereafter refer to as "new data", has been clearly recognized, difficulties remain, as there is little empirical evidence on how cities are using the new data to monitor urban sustainability, particularly for *SDGs*. Presently, traditionally collected data such as official data from statistical offices and other authorities, including international organizations, are used to evaluate *SDG* approaches (Fritz et al. 2019). This is likely caused by the extant guidelines, which mostly leverage official data for political, regulatory and availability reasons (Bertelsmann Stiftung et al. 2020, Siragusa et al. 2022). Moreover, voluntary local reviews, which are published by cities for local *SDG* assessment, mainly use official data.

This paper brings together smart city approaches and sustainability data research and adds case study evidence to the debate. By combining work from critical data studies with the urban sustainability literature, we aim to identify the potentials and pitfalls of using new local data in urban monitoring systems. In addition to conceptual and literature-based reflections, the paper takes an empirical approach. Our research questions include "What opportunities do new data offer for urban *SDG* monitoring systems?," and "What are the challenges of using new or complementary unofficial data sources (such as those collected in smart city approaches) in *SDG*-related urban monitoring systems?" To answer these questions, this paper is divided into four parts. The upcoming section provides an overview of the relationships between data and urban development, followed by an examination of the challenges of data-driven urban monitoring systems. Then, the case of Treptow-Köpenick is provided. Our overarching purpose is to contribute to the emerging debate on smart city development and sustainability by describing how policymakers and researchers should (re)examine the use, treatment, distribution, accessibility, and visualization of available official and unofficial data for sustainable urban development.

Better data, better cities?

Urban data include all digitally available information of general relevance to urban social settings, which can have different origins, ownerships, and management styles (Schieferdecker 2021). Cities have long collected and processed similar data, but new technologies have driven changes in their use. New sources and subsequent analysis and visualization methods have emerged, and their uses currently include built environment monitoring, real-time energy demand visualization, and air quality reporting. Compared with traditional data curation methods, new data sources and types offer advantages of cost, collection frequency, timeliness, and geographic scope (Fritz et al. 2019, Fraisl et al. 2020).

The ubiquitous presence of new data sources (e.g., sensors that use the Internet of Things) and modern aggregation and visualization methods is expected to lead to data-rich and -driven forms of urban management, but it comes with challenges and risks (Kitchin 2016) in terms of security, privacy, and ownership (Pagliarin 2021). Moreover, there are many unknown risks about the non-objectivity of data in general (Frith 2017) and the exclusive focus on particular types of knowledge (e.g., instrumental vs. scientific; Kitchin 2016).

Accordingly, authors from data science studies argue that the composition and use of data must be critically analyzed. D'Ignazio and Klein (2020) showed that ignoring gender-related datasets leads to biased conclusions in data analytics. Törnberg and Uitermark (2021) argued for a new heterodox computational social science that highlights the risks of molding data analytics into a new digital capitalism. Relatedly, Zuboff (2019) linked the role of surveillance data in capitalist societies to high exploitation risks. Safransky (2020) describes how algorithms in data-driven assessment tools for urban investment decisions lead to the racialization of space and spatialization of poverty. MacFeely (2019) and Ilieva and McPhearson (2018) identified new legal, ethical, technical, and reputational pitfalls to many of these technologies.

Hence, it is an obvious fallacy that "better data" will automatically lead to "better cities." Conventional wisdom states that

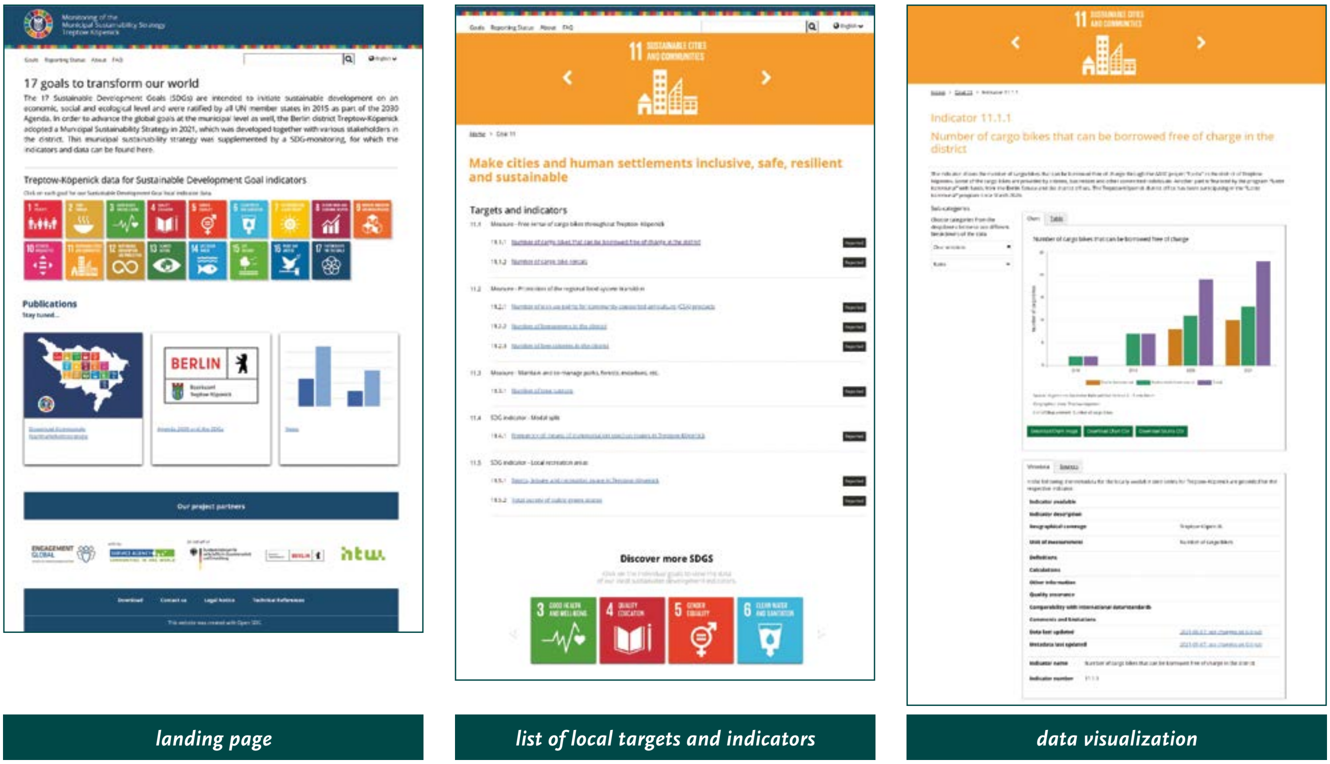

FIGURE 1: Treptow-Köpenick's *Sustainable Development Goal* monitoring system: the platform consists of a landing page with a general introduction and a list of all *Sustainable Development Goals (SDGs)* (left), and subpages listing the targets and indicators for each *SDG* (center) and showing the specific results for each indicator (right).

more precise and accurate data and simpler, more powerful interfaces will be inherently beneficial to society because better policy decisions and emergency measures can be made (Holden 2013), for example in terms of urban energy consumption and traffic flow assessments. The assumption that "better leads to better" is an instrumentalist and positivist paradigm that is reflected in the United Nations' *2030 Agenda*. A notable example is the postulated assumption of "Better data for a better planet and better lives" (Daguitan et al. 2019, p. 71). Great care is needed going forward to ensure that the new data are not used exclusively for instrumentalist (Kitchin 2016) or positivist (Pfeffer and Georgiadou 2019) outcomes. Moreover, in an ever-changing global policy environment, the use of data analytics in sustainability fields is increasingly assigned a discursive-interpretative role, whether in education, politics, or society at large (Pupphachai and Zuidema 2017).

Data and monitoring systems

The role of monitoring systems in sustainable urban development is to make decision-level information more accessible and transparent by collecting and analyzing the appropriate data and selecting the best indicators for measuring change. This is functionally fine, but it is less clear how well the existing data platforms can support these objectives (Kitchin 2016). The collection and curation of urban sustainability data are complex and confusing, especially when deciding the best way to apply them to measuring the achievement of *SDGs* (Siragusa et al. 2022). Hence, systems must not be designed in isolation as the relevancy of the data and the tenets of society are highly dispersed and interconnected.

Notably, the desired indicators must be accessible from the collected data. As such, the indicators should be socially derived. Therefore, the mere existence of unused or unresolved urban data features in a dataset is insufficient for creating new indicators. Moreover, it is dangerous owing to the several fallacies and biases discussed above. Michalina et al. (2021) argued that a city's specific conditions and goals must be considered when defining sustainability indicators. Accessibility is also crucial for socially beneficial data monitoring. For example, if users are provided raw data, they can assess the development of certain indicators without depending on the interpretations of others. In this context, Schieferdecker (2021) highlighted the importance of open data, as defined for example in the eight open data principles.[1] That is, data must be complete, disaggregated, timely, freely accessible, published and machine-processable, non-discrimina- >

1 *https://opengovdata.org*

tory, non-proprietary, and license-free and reusable (Lwin et al. 2019). Furthermore, the existence of metadata and their accessibility are equally important for understanding the information retrieved. For example, reducing urban CO_2 emissions is important for achieving *SDG 13,* but emissions are currently measured in different ways based on the necessary theoretical assumptions and aggregation requirements. Therefore, appropriate disambiguation information should be provided in the metadata.

The origin of the data must also be considered. Recently, new data sources have emerged that have the potential to support smart cities, such as citizen science data and sensor data (Cutter 2021). This provides a potential major shift in the traditional role of the public sector from exclusive data consumers to producers (e.g., crowdsourcing), in which private actors (e.g., individuals, companies, and civil organizations) provide the data. Because cities engaged with *SDG* monitoring tend to rely only on official data, the potential benefits of other types and sources of data (so-called unofficial data) require examination.

Importantly, data are not to be considered neutral or "raw," as they originate from and affect the context of the given societies. They are shaped by beliefs and biases (Luque-Ayala and Marvin 2020), they reflect power inequalities, unequal access, and institutionalized justice systems (D'Ignazio and Klein 2020). This is even more applicable to private data sources, wherein issues of propriety, exploitation, profit, and confidentiality are paramount. In summary, urban monitoring systems must not be viewed as neutral technical assemblage but the result of complex interactions (Kitchin et al. 2015). Hence, even with suitable indicators, the context of the collected data and the purposes of their desired use must become part of the analytical framework (D'Ignazio and Klein 2020).

We must acknowledge the social complexities that influence the data, their metadata, and their interpretations so that production and use of new data for Sustainable Development Goals *monitoring can be fully understood as a social process rather than a purely technological one.*

The case of Treptow-Köpenick

Treptow-Köpenick is one of twelve districts in the Federal State of Berlin. The district is located in the southeastern part of the state and has a population exceeding 276.165. Districts have the status of municipalities, and their mayors and administrations enjoy certain degrees of autonomy. Treptow-Köpenick began developing a sustainability strategy in 2017 using *SDGs* to construct its framework. The effort entailed a lengthy participatory process that involved the public. The resultant strategy included 68 specific measures, such as the free rental of cargo-bikes *(SDG 11),* reduction of food waste in public schools *(SDG 3),* and a new climate protection vision *(SDG 13)*. Our research team was onboarded in 2019 and has documented the progress and lessons learned thus far. A formal strategy was adopted in 2021, and from this, the district has planned standardized but locale-specific data-driven monitoring systems that include extant sources and tools. The system was launched in February 2022[2] and contains 1. a landing page with a general introduction and a list of all *SDGs,* 2. the targets and indicators for each *SDG,* and 3. the specific results for the respective indicators (figure 1). Next, we describe our experiences with indicator selection, data collection, and data handling.

Methodology

The selection of indicators was closely linked to the district's *SDG*-based sustainability strategy. The district government and affiliated planners decided to focus on measure- and impact-related indicators. The former reflects the efficacy of related policy measures, and the latter reflects *SDG* attainment. For example, for *SDG 11,* the district established the "free rental of cargo bicycles throughout Treptow-Köpenick" measure, which is represented by the specific indicator, "number of cargo bicycles that can be rented free of charge in the district". Complementarily, the "modal split" indicator is used to measure *SDG* impact. The district's "municipal climate protection concept and climate protection manager" measure includes the measure-related "job shares for climate protection management in the administration" indicator and an index indicator on the topic of municipal climate protection. "CO_2 emissions" is an *SDG* impact indicator.

The indicator selection criteria were built around data availability and quality, in addition to the strength of their traceability to the district's sustainable urban development strategy. In addition, we analyzed whether or not actions taken by the municipal government can influence the development of a particular indicator. Some indicators often used in *SDG* monitoring, such as "funding for international development cooperation", depend on the national or federal state level, and the municipal level therefore has no authority to take action in this policy area. In this context, various existing *SDG* indicator reports from other cities were consulted.

2 *www.sdg-treptow-koepenick.de*

Official data (such as from the micro census) were solicited first, as they were readily accessible. Then, available "new data" sources were incorporated, which happened to reflect air quality, water quality, and traffic sensor data, to name a few. Part of the traffic data reflects cyclists per street per weekday, whose sensors were funded by the Berlin Senate, which collects this data and publishes annual reports. The figures from these reports are then fed into the monitoring system. As there is no interface between the Senate's data and the monitoring system, the system does not display real-time data, but uses data from the annual reports.

As the work progressed, it became clear that the official data were not as available as initially believed. Hence, the integration of unofficial data was greatly expanded. The district government and planners understood that this step would require the involvement and active support of both private citizens and local officials who had participated in building the sustainability strategy. Hence, the bulk of unofficial data was acquired from civil organizations, including schools and churches. For example, the *Mundraub Association*[3] provided crowdsourced data on edible plants in the district and their locations, and the *Foodsharing Organization* provided data on the amount of food saved (i. e., not wasted) in kilograms. Web-scraping techniques were also used to track the number of solidarity farming collection points across the district.

Owing to the heterogeneity of official and unofficial sources, metadata were added to all indicators to convey origins, collection methods, and data providers. Eventually, all indicators were publicly discussed using the *Adhocracy* platform, where individuals can provide comments vetted with researchers and policymakers. An attempt was made to take the suggestions into account in the final version of the monitoring.

After approval, the selected indicators and their data origins were published online using the *Open SDG* platform,[4] which was created through a collaboration between the UK Office for National Statistics, the US government, and the nonprofit Center for Open Data Enterprise. The results can be accessed worldwide for *SDG* reporting. Barcelona, Los Angeles, and Bristol, for example, use the platform too. The chosen technical solution was based on open data principles, meaning that all raw data and metadata in the system must remain accessible and processable by all users.

TABLE 1: Results of indicator selection.

INDICATOR/ DATA	MEASURES	IMPACT ON SDGS	TOTAL
official data	26	21	47
data from civil society organizations	15	9	24
no data			16
TOTAL			**87**
NEW DATA SOURCES			
sensor			4
crowdsourcing			3
webscraping			1
TOTAL			**8**

Results

A total of 87 indicators were selected from the above processes using anonymized and highly aggregated data. In total, 47 datasets came from official data sources, and 24 were unofficial. Crowdsourced, sensor, and web-scraped data were used to support eight indicators. Out of 87 indicators, 16 could not be suitably supported by the data (table 1).

Discussion

The theoretical debates on the use of smart city data to monitor the *SDGs* mentioned above emphasize that new data sources allow for more accurate monitoring, however, the case of Treptow-Köpenick district of Berlin clearly illustrates the many difficulties involved in balancing official and unofficial data sources. Notably, the selection and availability of indicators, the need to contextualise data collection and the inclusion of different data providers proved challenging.

The selection of appropriate indicators and the search for suitable data was demanding, as there were large gaps in official data. The integration of unofficial data and the involvement of civil society actors was a logical consequence for all stakeholders in the project.

During the development of the monitoring system, shortcomings in the types and sources of data (traditional and "new" types of collection, official and unofficial data sources) became apparent. For example, CO_2 emission data were not aggregated at the district level. Hence, Berlin-level total emissions were divided proportionally, which relied on assumptions of scope and source. This means that the data for Treptow-Köpenick is heavily influenced by the other eleven districts of Berlin.

It was difficult to track and measure the quality of the data provided by civil organizations, and the collection methods varied among providers. For example, one indicator is the number of bicycle trips in the Stadtradeln bicycle competition. Such crowdsourced data often lack measures of reliability and accuracy. More difficult was the translation of qualitative report data into basic indicator parameters. For example, the indicator that uses data on the number of racist, antisemitic, homophobic and right-wing extremist incidents per year in Treptow-Köpenick. People can report such incidents digitally or in person to a civil society organization that forwards the data to the monitoring system. Importantly, it is nearly impossible to know the true number of unreported incidents, but we know that it is "high." The role of metadata in these cases allows platform users to be aware of the origin and shortcomings.

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3 *www.mundraub.org*
4 *www.open-sdg.org*

The purpose of the case study was to inform the development of a monitoring system that could provide the district's population with the opportunity to follow the progress meeting the *SDG* measures. Through participatory events, attempts were made to initiate a joint *SDG* monitoring system. However, engaging and retaining the interests of local actors proved to be very difficult. Although many private citizens and agencies were willing and active in providing data, the labor needed to adequately process the data was unforthcoming. As a result, D'Ignazio and Klein's (2020) call to reduce the inequity of data-related social monitoring and decision-making methods fell short, and the need to illuminate the extant power imbalances was only partially met. The process of contextualizing data was not as transparent as we had desired. Nevertheless, data-searching and collaboration efforts have led to the establishment of new contacts and partnership opportunities. In summary, the case presented provided the beginning of a joint dialogue with the district.

The overarching guidance to the district was the *2030 Agenda* and the desire to pursue *SDGs*. Accordingly, the continued development and maturation of the monitoring system will reflect this agenda as it changes and grows. Over time, more clearly quantifiable targets and thresholds will be set for the indicators as they mature. The lack of precise target values was not unexpected, and it provided demand signals for roadmap development, which must be facilitated politically by district- and state-level sustainability strategies.

Concluding remarks

The use of smart city data (i.e., unofficial data from diverse sources and providers, often collected more frequently) provides exciting new opportunities for municipalities as they engage with local stakeholders to promote public participation in *SDG* monitoring. Notably, this process is not straightforward, and one must account for the different perceptions and values of sustainability of the many stakeholders as well as various practical constraints. Many authors have emphasized the theoretical potential of harnessing emerging data for smart city approaches and sustainability measurement. Our empirical example demonstrated the pitfalls of this complexity and some of the associated technical barriers (e.g., lack of data interfaces). It remains difficult to assess data quality at the city level, and the time and resources needed from public and private sources are daunting. Illuminating the barriers is a prerequisite for overcoming them, and our results frame the problem for future research and actions. Notably, our findings highlight the critical role of metadata in determining the utility and feasibility of indicator identification and definition. As noted, data are not neutral items; they are socially and politically constructed and reflect issues of power and existing biases in society.

Metadata are therefore an integral part of Treptow-Köpenick's monitoring system, as it allows potential shortcomings, underestimations and other forms of data inaccuracy to be made visible and explained. This transparency is particularly necessary for the new, unofficial data sources.

The Treptow-Köpenick district case clearly shows that in order to use new and unofficial data in *SDG* monitoring, compromises are required. Rather than viewing new data as a purely neutral technological set of figures, we must acknowledge the social complexities that influence the data, their metadata, and their interpretations so that production and use of new data for *SDG* monitoring can be fully understood as a social process rather than a purely technological one.

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Using augmented reality in urban planning processes

Sustainable urban transitions through innovative participation

The use of augmented reality applications in urban planning improves the quality of participation processes and contributes to sustainable city development. However, as our case studies also show, these potentials are not fully exploited yet as augmented reality is not yet used in all planning phases.

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Using augmented reality in urban planning processes. Sustainable urban transitions through innovative participation
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Abstract
Sustainable urban development requires innovative approaches and concepts that involve people not only in planning processes but also in influencing the design of urban space. Modern formats, such as augmented reality (AR), can help to increase the motivation for participation and present different planning concepts more realistically through different forms of visualization. Based on case studies in Vienna, Austria, and Lucerne, Switzerland, we examine AR applications in planning participation and discuss the innovative nature of these applications. We show that the use of AR not only increases the motivation of the population to participate in planning processes but also increases the quality of participation processes and can, thus, trigger a sustainable transformation of cities.

Keywords
augmented reality, digital participation, impact on urban planning, sustainable urban transitions, urban planning, virtual reality

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Urban planning can be understood as the process of making decisions to shape and guide the future of our cities – for example, in terms of settlement structures, infrastructures, buildings, and open spaces. For this purpose, planners develop planning concepts and strategies and then present and discuss initial ideas and proposals with interested stakeholders and politicians. In doing so, planners are required to take into account the broader social, ecological, technical, and economic trends and developments as well as locally specific conditions for housing, work, culture, and leisure. Thus, such concepts and plans may include ideas to improve the health conditions or the quality of life in specific neighborhoods by, for example, redesigning streets to foster cycling, building more affordable housing, or increasing the number of parks for families in working class neighborhoods.

Numerous actors with different interests are involved in these urban development processes, with or without prior knowledge of legal regulations, planning instruments, ecological conditions, the cubature of buildings, or similar aspects. Hence, the (visual) information provided to participants needs to be easy to understand (Kikuchi 2022). In this context, spatial imaginations of urban streets, buildings, and neighborhoods have played a major role in public participation in urban development (Höhl and Broschart 2015). Visualization is considered the key for successful participation, as it provides all participants with a shared basis or language (Al-Kodmany 1999, 2002). Consequently, appropriate visual representations are crucial for the building of public opinion and decision-making (Boos et al. forthcoming).

Traditional and analog ways of visualizing and communicating new planning concepts and projects include the preparation of maps, blueprints, and paper-based drawings, often accompanied by photographs and/or physical models to optimize illustrations of the planned project. The succeeding generation of planning or visualizing instruments then incorporated geographical information services (GIS) and computer-aided design (CAD) to map land use, visualize the dimensions of design in a digital environment, and offer perspective three-dimensional (3D) sketches. Finally, 3D city models, based on 3D geospatial data, reproduce the physical city in a virtual world (Al-Kodmany 2002, Billger et al. 2017, Kikuchi et al. 2022, Rohil and Ashok 2022, Wilson and Tewdwr-Jones 2022). As ongoing developments in numerous European cities indicate, "[l]ocal governments [increasingly] use 3D city models for urban planning and environmental simulations such as estimating the shadows cast by buildings [or] investigating how the noise from traffic propagates through a neighborhood" (Biljecki 2017, p. 3). Consequently, visualization tools such as AR have become an essential platform for co-designing with residents in urban spaces (Ruohomäki et al. 2018), highlighting 3D visualizations of intended urban development plans or projects contextually in physical spaces, and simultaneously, co-designing urban interventions in-situ (Lock et al. 2019).

However, existing studies and reports on AR tools and applications often refer to technical prerequisites, application possibilities, etc. (e.g., Beneš et al. 2022, Boos et al. forthcoming, Höhl and Broschart 2015), include cross-analyses of existing publications on AR (e.g., Rohil and Ashok 2022, Wolf et al. 2020), or present AR applications with reference to specific topics (e.g., culture, tourism, transport planning) (Fegert et al. 2021, Kikuchi et al. 2022). Thus far, only a few studies have focused on the use of AR in urban planning processes (e.g., Saßmannshausen et al. 2021, Schürmann et al. 2021). This is the starting point for this article, which considers the following research questions: How is AR used in planning practice? For what purposes and in which planning phases is it used? To what extent can AR contribute to the sustainable transformation of cities, particularly with regard to a more balanced participation of actors and to more transparent participation?

Augmented reality as both a digital visualization and digital participation tool

We see AR as both a digital visualization tool and a digital participation tool. AR was first mentioned and defined by Caudell and Mizell (1992, p. 660) as a technology which "is used to 'augment' the visual field of the user with information necessary in the performance of the current task". This distinguishes AR from VR, which can be described as "a computer-generated artificial environment that makes the users of the device feel as if they are in a different artificial world" (Rohil and Ashok 2022, p. 1, see also Schürmann et al. 2021). In contrast, in AR the representation of digital objects overlaps with reality, thereby implying that actual situations are enriched with additional digital information (Kikuchi et al. 2022, Zeile 2017). In this manner, for example, a digital sketch of planned buildings, streets, or public spaces is projected into the actual environment in real time (Zeile 2017, p. 619, Rohil and Ashok 2022, p. 1).

According to Tomkins and Lange (2020, p. 372), AR offers a novel tool for visualizing a wide variety of data. Thus, AR enables planners, policymakers and other stakeholders such as citizens to experience and better understand the intended changes in the built environment and to identify potential conflicts before a development is implemented in practice. However, a review of existing studies (Schürmann et al. 2021, Fegert et al. 2021, Beneš et al. 2022, Wolf et al. 2020) reveals that AR applications have often been used with regard to specific projects (e.g., a building to be constructed, a street or park to be redesigned, etc.). In these cases, it appears that AR is used when realizing a planned project (but the project itself is no longer under discussion) for presenting variations in the design of the project (e.g., positioning of furniture in a public space, etc.) to raise awareness and acceptance of the intended project. Here, AR – with its different levels of detail (e.g., with regard to building cubature, façade design, shading, etc.) – enables a rather realistic depiction of the intended structural-spatial development (Boos et al. forthcoming). However, whether or not AR applications are also suitable for the discussion on possible planning alternatives (e.g., for the intended residential use of an inner-city brownfield site) at the beginning of strategic planning processes (where the outcome of planning is still largely open) remains debatable.

Providing AR visualization in planning processes can increase motivation and willingness to become involved in participatory events, as AR systems provide new sources of information to support decision-making in the process (Boos et al. forthcoming, p. 5). According to Tomkins and Lange (2020, p. 372), AR "open[s] up new modes of communication and visualization to enhance the widespread practice of model making and could be a flexible tool for designers, students, and stakeholders to analyze and communicate evolving or competing designs in a dynamic context". Therefore, AR visualizations offer manifold, often playful and captivating, interactions with relevant stakeholders (Sankowska 2020). This is in line with the results of other studies (Saßmannshausen et al. 2021, p. 252, Awang et al. 2020, pp. 53 ff.) that highlight how AR can enhance motivational effects on stakeholders, particularly on underrepresented groups such as young people, thereby encouraging participation in planning processes via gamification and other playful approaches.

Further, Awang et al. (2020, pp. 53 ff.) demonstrated that AR applications as a basis for (digital) participation can increase the willingness of stakeholders to participate in public planning processes. They indicated that people prefer the use of 3D objects and the 3D-visualisation of surroundings and building cubature rather than 2D plans (Awang et al. 2020, pp. 54 f.). The selected level of detail of the displayed objects in an AR application also appears to make an impact on the users and, thus, influence the participation process. For example, an AR visualization with a low level of detail could provide a less clear picture of a design, thereby making it easier to engage the public in an early participation process (Boos et al. forthcoming, p. 25). Furthermore, more detailed visualizations can be used to provide a more concrete picture of a project in subsequent planning phases and "could be used for purposes where authorities wish to make a definitive commitment" (Boos et al. forthcoming, p. 25). However, there are very few studies that empirically analyze the extent to which AR can contribute to more effective and efficient

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ways of public participation in planning processes – this relates primarily to the role of initiating and participating actors, the embedding of AR applications in planning processes, and the presentation of planning content in AR presentations. Therefore, the extent to which AR can "assist decision-makers, planners and communities to collectively plan and engage in creating sustainable, liveable and productive cities" remains unclear (Lock et al. 2019, p. 1).

Research design and methodology

To be able to capture current AR applications in urban development processes, we conducted an Internet-based desktop research and literature analysis as well as a case study analysis of two AR-based planning processes in practice. The literature review concentrated on published articles in the *Web of Science, ScienceDirect,* and *Scopus* databases. By using specific search terms such as "3D visualisation", "augmented reality", "virtual reality", "digital participatory planning", "virtual urban planning", "virtual urban reality", and "digital twin", we were, as a first step, able to identify relevant articles. In a second step, we read the abstracts of the identified articles to allow a profound selection of papers that, on the one hand, explain how AR applications work and, on the other hand, have already made initial impact assessments on the use of AR. Thereafter, we selected articles in which the terms and concepts in the abstract strongly overlap with the subject of our study (e. g., articles presenting case studies where AR has been used for a sectoral planning process, etc.). Finally, we selected 30 articles and analyzed them with the aim of deriving criteria for the analysis of the case studies in order to be able to assess the potentials and weaknesses of AR in urban development processes.

According to the literature analysis (see above), we derived three research dimensions that are highly significant for the use of AR applications in practice but have not been researched adequately thus far. This includes stakeholder constellations, transparency, and the presentation of planning content. *Stakeholder constellations* analyze the role of the actors who develop and use AR applications (e. g., urban planning departments, start-ups, research organizations) as well as interactions with potential users (other municipal departments, inhabitants, etc.). This must also be considered in relation to *transparency*. Here, the following aspects are highly relevant to understand the use and impact of AR applications in the planning process: 1. the embeddedness of the AR application in the entire planning process (as well as the integration with analog participation formats); 2. the planning phase or the point in time at which the AR application is used in the planning process (rather open participation in an early planning phase or rather limited participation in a subsequent participation phase); and 3. simple access to and use of the application. The *presentation of planning content* includes the depth of representation and the (visual) innovations that AR applications can bring to consultations in the planning process. What is also of relevance here is which contents are visualized in the application (and in what manner) and which are not, particularly with regard to sustainable development.

We then applied these dimensions in our case study analysis. The identification of relevant case studies for the in-depth analysis of AR applications followed a rather pragmatic research approach, thereby implying that we searched for cases where we could test AR applications in practice and where we could interview the main actors regarding their experiences with the AR applications. This included, among others, planners, app developers, and researchers. On this basis, we selected case studies in Austria (Vienna), Germany (Hamburg, Karlsruhe), and Switzerland (Lucerne), where AR applications have recently been applied or are currently being tested in urban development processes. The case study analysis includes guideline-based expert interviews with involved municipal representatives, representatives of AR companies, and researchers involved in developing and implementing AR in the selected cities. Overall, we conducted nine interviews to identify the opportunities and challenges of AR applications in urban planning processes. Five interviews were linked to the two case studies in Vienna and Lucerne, which are examined in greater detail in the following paragraphs. We selected these two cases because the two AR tools developed here relate to different application areas and dimensions and have only recently been tested in practice. The interviews are evaluated using qualitative content analysis in accordance with Mayring (2015). In this context, the results of the interviews in Vienna and Lucerne were also compared with the results of the interviews from the other cities.

In both cases, the initiators of the AR applications also conducted their own empirical surveys, the results of which were available to us. These results, particularly those pertaining to user groups and user satisfaction, provided further empirical findings that we used to assess the impact of AR in the two case studies. In addition, the case study analysis consists of our own experiences with the respective AR applications (particularly regarding issues such as functionality, degree of presentation – what is presented and what is not –, susceptibility to interference, and comprehensibility), which we were able to gain in the course of self-tests of the AR tools on site. Further, we recorded and evaluated our self-tests in accordance with the methodological procedure for on-site visits. Based on the combination of the results from the expert interviews, the supplementary local surveys and documents, and the self-tests, we then evaluate the case studies before we finally discuss and evaluate the overall potentials and weaknesses of AR applications in planning processes.

Making climate effects visible via augmented reality – Bernardgasse in Vienna

The first case study is an AR application for the redesign of Bernardgasse in Vienna, Austria. The water pipes in Bernardgasse require renewal and, thus, the district authority is taking the opportunity to redesign the entire street with an eye to the future. Currently, the one-way street is characterized by historical residential block perimeter development (figure 1).

The street is a single lane one, the sidewalks are narrow, and parked cars make it crowded, so there is little space left for public use. Bernardgasse is barely landscaped, thereby making it rather warm in the summer (GLARA Forschungskonsortium et al. 2021, pp. 5 f.). The city has already developed initial concepts to make the street more climate-friendly and sustainable through green structures. To illustrate the impact of greening on temperatures, an initial participation process with various analog events and an AR application was initiated in a comparatively early planning phase between October 14 and November 7, 2021. The target group for participation was the immediate neighborhood with residents of Bernardgasse and adjacent side streets. The AR application was developed and tested as part of the *GLARA* research project[1], a consortium comprising different partners such as the seventh Vienna municipal district, architecture and landscape architecture companies (superwien urbanism ZT GmbH and Green4Cities GmbH), a company specializing in the development of digital visualization tools (Fluxguide Ausstellungssysteme GmbH), and an international competence center for urban green infrastructures (tatwort Nachhaltige Projekte GmbH) *(stakeholder constellation)*.

The participation was organized by the *GLARA* project consortium and implemented by using different (analog and digital) methods, which included a "kick-off event", "information points", the "*GLARA* app", and a "survey" (GLARA Forschungskonsortium et al. 2021, pp. 10–13). The *transparent participation process* began with an on-site kick-off event on October 14, 2021. The event was attended by approximately 80 residents, who were involved through "emotional mapping" to communicate their wishes and ideas on the topics of 1. microclimate, 2. quality of stay, 3. traffic and street space (GLARA Forschungskonsortium et al. 2021, p. 10). In addition, their wishes and requirements for the redesigning of the street were considered in small groups. Subsequently, information points were set up along Bernard- >

1 The *GLARA* research project *(Green Living Augmented + Virtual Reality)* aims to create a low-threshold participatory planning process that enables and supports the design of green spaces with the participation of all stakeholders. Therefore, *GLARA* develops various analogue and digital participation formats in order to activate different stakeholders. These formats and tools are currently being used and tested in two case studies in Vienna for the redesign of public spaces (Green4Cities GmbH 2022).

FIGURE 1: Visualization of heat stress, that is, temperatures in Bernardgasse, Vienna, AT, in order to sensitize residents to climate-adapted urban development. Source: *www.fluxguide.com/puls/glara-kick-off-in-der-bernardgasse*.

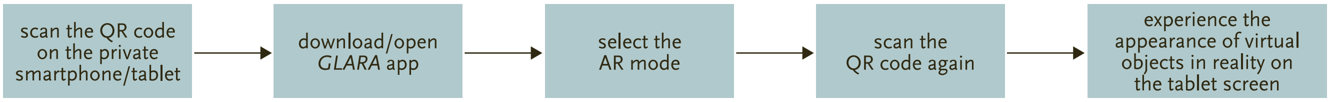


FIGURE 2: Access to and use of an augmented reality (AR) application in Vienna, AT (schematic diagram).

gasse between October 18 and October 22, 2021 (GLARA Forschungskonsortium et al. 2021, p. 12). A total of 90 participants took advantage of this opportunity and contributed additional ideas to the process.

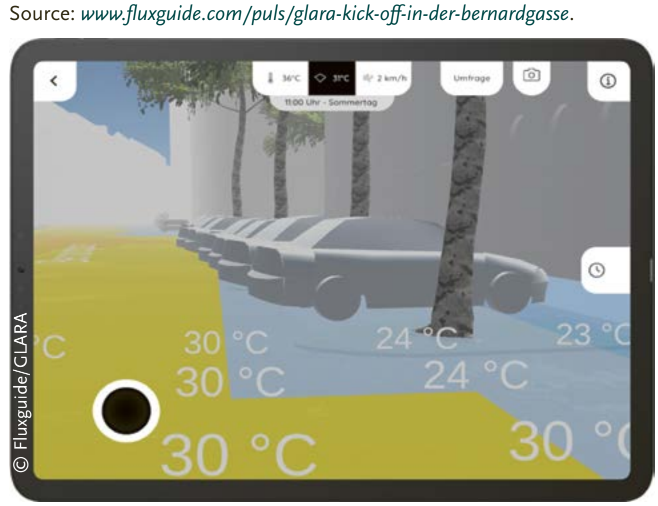
At the same time as the kick-off event, the *GLARA* app was released – an AR application that enabled the public to digitally experience the climatic impacts and effects of urban planning measures for sustainable urban development on hot summer days as well as the actual state of the microclimate in Bernardgasse during the participation phase (GLARA Forschungskonsortium et al. 2021, p. 13). The app was linked to the survey on the redesign of Bernardgasse, thereby providing participants the opportunity to comment digitally on the process and intended planning options in the period from October 14 to November 7, 2021. Further, individuals could participate in the survey not only via the *GLARA* app but also via a desktop application, and in print format. A total of 172 people completed the survey (GLARA Forschungskonsortium et al. 2021, p. 13).[2] Of the 164 responses[3], the age group of 30 to 44 years was dominant, accounting for 45% of the participants. This was followed by those aged 45 to 59 years, accounting for 23% of the participants. In addition, those aged between 20 to 29 years accounted for 17% of the participants and those aged 60 years or over accounted for 13% of the participants. It is striking that the group of younger people (19 or younger) is clearly underrepresented in the participation process, accounting for only 2% of the participants (GLARA Forschungskonsortium et al. 2021, p. 15).

The *GLARA* app was the essential tool for conducting digital participation via AR (figure 2). It was publicly accessible and can be downloaded from the Google Play Store (Android) or the Apple App Store (iOS) to be installed on private devices (smartphones or tablets). However, no smartphones or tablets were provided to the public, which is considered a hurdle for an open participation process, as people without a terminal device and older groups of people may, therefore, have found it difficult to participate. It was also observed that the functionality of the application cannot be guaranteed on all smartphone models. The positioning of the AR display employed marker-based access, where users scanned a QR code in the form of a street sticker to calibrate the visualization. This calibration was intuitive and caused no technical problems in the self-test conducted by the authors – by focusing on the marker with the tablet camera, the calibration was completed within a few seconds.

In the AR application, urban planning options are displayed in different variants and scenarios with reference to the climatic situation in Bernardgasse *(presentation of planning content)*. Beginning from a status quo with current climate data, variables that simulate different scenarios of structural or open space planning interventions can be selected (e.g., various forms and intensities of greening, reduction of parking places) and their microclimatic effects can be witnessed (figure 3). A setting for different times of day or night and scenarios regarding the position of the sun is also enabled in the *GLARA* app. This makes it possible for the public to experience the effects of urban planning measures related to climate adaptation and their impact on the (perceived) temperature (in °C) in Bernardgasse (but the participants cannot develop their own drafts or planning options). Thus, the representations of climate data in augmented reality illustrates the effect of specific climate adaptation and mitigation measures. Through this, the effects of the planning interventions on the microclimate can immediately be experienced and the understanding of specific approaches to climate-adapted and sustainable urban development is promoted (as part of the knowledge transfer). All participants were able to evaluate concrete interventions from the same perspective.

Overall, a transparent approach to citizen participation is evident in the first participation phase for the redesign of Bernardgasse in line with sustainable urban development. In public par-

FIGURE 3: Visualization of temperature differences with and without planting in Bernardgasse, Vienna, AT, using augmented reality. Source: *www.fluxguide.com/puls/glara-kick-off-in-der-bernardgasse*.



2 Of the 172 participants in the survey, 135 people participated via web browsers, nine used the printed form, and 28 participated via the *GLARA* app (GLARA Forschungskonsortium et al. 2021, p. 14). This indicates that it was possible, in a short period of two weeks, to introduce the AR application and to actively use it in the planning process. Simultaneously, it becomes evident that other participation formats have a longer range thus far, thereby implying that AR applications should be linked with other participation tools.

3 Of 174 participants in the survey, 164 persons answered this question.

ticipation, both analog and digital formats are introduced in the participation process, both of which can complement each other in a meaningful manner. The entire participation phase was stringently organized and communicated to the residents via a kick-off event, flyers, and visibility in the public space through various information points. Thus, the *GLARA* app strongly supported the participation process and the transfer of knowledge of climate data to the population via the simulation of microclimatic effects. Moreover, within the *GLARA* app, there were opportunities for the public to participate in the survey on the participation process in order to comment on the intended plans and options. Overall, the participation process in Vienna is characterized by a combination of different approaches, both analog and digital, which complemented each other. This makes the overall participation process broader, with the aim of responding better to the disadvantages of classic formats and enabling the involvement of multilayered population groups.

Making future street design visible via augmented reality – Bahnhofstrasse and Theaterplatz in Lucerne

The case study in Lucerne, Switzerland, was a research project in cooperation with the Civil Engineering Office of the city of Lucerne and the research groups *Visual Narrative* and *Immersive Realities Research Lab* of the Lucerne University of Applied Sciences and Arts. The aim was to free Bahnhofstrasse and Theaterplatz from motorized traffic, to redesign the public space (planting 30 new trees, etc.) and to upgrade the street with an underground bicycle station that also provides a direct connection to the main station (which was rejected in a referendum in February 2022) (City of Lucerne 2022). Due to its location in the city center, the public interest in this project is comparatively high. The aim of the AR-based participation process in September 2021 was to make the various options and solutions accessible to the broad public during the planning process and to communicate with them in a transparent and comprehensible manner (Schürmann et al. 2021, p. 43).

The first plans and concepts for the redesign of Bahnhofstrasse were already developed in 2014. In 2016, an urban planning competition took place, in which various planning options for the designated area were presented. On this basis, the Civil Engineering Office developed the final plan, which was then presented to the public in September 2021 as part of the formal planning process (City of Lucerne 2022). During the preliminary considerations for the pending participation process in early summer of 2021, a private meeting took place between members of the Civil Engineering Office and the University of Applied Sciences and Arts Lucerne (on the initiative of a leading administrative manager of the Civil Engineering Office). By analyzing the *stakeholder constellation,* two aspects became decisive ones for the city administration to become involved in such a participation format. First, the open and uncomplicated attitude of individual members of the Civil Engineering Office. Their focus was on testing new technologies like AR and to see if they could offer benefits for public participation processes (the risk of failure was accepted). Second, the "strategy for shaping digital change in the economy, society, and public administration" of the Canton of Lucerne, which at least established the foundation for innovative and digital participation formats in the city of Lucerne. This gave rise to the idea of using an AR application to support the participation process and to present the intended planning in a more comprehensible and understandable manner. The use of AR at this comparatively late stage of the planning process was to present the selected planning alternative and obtain citizens' approval for it before the city council could subsequently decide on and implement this alternative (figure 4, p. 60). The discussion of other ideas or alternatives via AR was not foreseen at this stage.

After the public was informed through various media such as the newspaper, the internet and posters in public spaces, citizens were able to participate in guided tours of Bahnhofstrasse with the help of AR in September 2021 *(transparent participation process)*. The target group for the participation process included people affected by the plans and local citizens, politicians, and other interested parties. People of different ages from these groups were involved during the guided tours; this made it evident that younger people, in particular, could be motivated to participate at the guided tours through the AR-based participation. Almost 28% of the participants were between 18 and 35 years old, 60% of the participants were between 36 and 55 years old, and 12% were over 56 years old (Schürmann et al. 2021, p. 47). However, compared to analog participation formats, the overall number of participants was not more culturally or socially heterogeneous.

Further, in order to be able to use the AR application, guided tours were offered by the project partners *(transparent participation process)*. On these tours, participants were provided with tablets and could use the mobile devices to virtually view new design elements like seating, bike racks, and plantings as 3D visualizations in the public space (Lucerne UAS 2021). As the project partners were in favor of simple and low-threshold access, the AR application was installed on these tablets; there was no need to download apps or register with personal data to use the application (figure 5, p. 60). In case of technical questions or problems, members from Lucerne University of Applied Sciences and Arts or the Lucerne Civil Engineering Office were available on site. The only step that the participants had to take in order to be able to see the AR representation with positional precision was to calibrate it to pre-defined markers (viewpoints). Switching between different views within the application also involved no time delay. Further, viewing different variants from different perspectives formed the heart of the AR application. Within the application, there were technical options that enabled participants to make a note of their own opinions verbally or in writing and to create their own designs. Overall, the AR application was positively evaluated by the participants in a non-representative survey conducted by the organizers in Lucerne; moreover, >

FIGURE 4: Redesign of Bahnhofstrasse, Lucerne, CH: virtual objects such as the new line of trees and seating are projected into the actual environment. Source: *https://www.hslu.ch/de-ch/hochschule-luzern/ueber-uns/medien/medienmitteilungen/2021/08/19/ar-umgebung-bahnhofstrasse*, modified.

there were no complaints regarding the technical application (Schürmann et al. 2021, pp. 47–48).

In the AR application, the redesign of Bahnhofstrasse and Theaterplatz is visualized by displaying the locations of objects, such as trees, seating, and bicycle stands *(presentation of planning content)*. The participants can switch between different display types or variants in the view. The level of detail is very high and, thus, the representation of the individual objects is rather detailed. Even the shadows are visible, thereby making the virtual objects appear even more real. Further, there is no setting for different times of day or night or weather scenarios, which could have enabled planning designs to be visualized in different lighting situations (figure 6). Nonetheless, a fusion between reality and virtuality is enabled on mobile devices. Only little negative feedback was received for participation exercises using AR applications as compared to that for analog participation exercises without digital technology. Analog participation formats often present 2D plans or renderings that participants need to understand despite lacking planning knowledge. Such images may be interpreted in different ways. However, the AR applications enabled discussions between different stakeholders about the planning content and were factual, as everyone had the same perspective on the plans or digital perspectives, thereby implying that the intended planning options were transparent for all. Thus, the representations in AR objectified the discussions among the various stakeholders. Further, unsubstantiated claims and complaints regarding planning situations, which are often otherwise made in participation processes, played no role here. All stakeholders were able to discuss concrete issues on the same basis, which resulted in dynamic discussions.

Overall, the participation in the redesign of Bahnhofstrasse and Theaterplatz in Lucerne can be considered a good example of participation in urban planning with the help of AR. According to a survey on the participation format (Schürmann et al. 2021, p. 47), the combination of using the AR application as well as having the plans and posters simultaneously available in printed form was preferred by most participants. The AR application is intuitive and easy to use. Moreover, the technology works without interference. The planning content is mapped transparently and has, thus, contributed to the success of the participation process as the technology supported face-to-face discussion of

FIGURE 5: Access to and use of an augmented reality (AR) application in Lucerne, CH (schematic diagram).

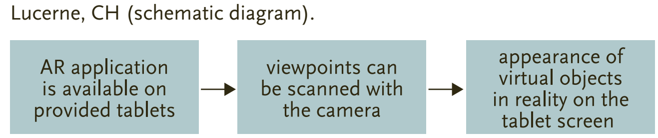


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FIGURE 6: Plants and seating can be displayed as one of three variants (A, B, C), along with shading options and a playground, as virtual objects in real space in Bahnhofstrasse, Lucerne, CH, using augmented reality. Source: *https://www.hslu.ch/de-ch/hochschule-luzern/ueber-uns/medien/medienmitteilungen/2021/08/19/ar-umgebung-bahnhofstrasse,* modified.

the planning content not only among the participants but also with members from the Civil Engineering Office. However, the guided tours also "excluded" people who could not attend on the dates on which the tours took place. If the AR application had been made available on tablets and private smartphones, people would have been able to participate at any time. Furthermore, it would be helpful to integrate a participation tool into the application that not only enabled viewing but also created a collection of opinions to identify further ideas for implementation. In general, the AR application was used at a comparatively late stage in the formal planning process and was exclusively concerned with concrete design issues. However, the planning alternative itself was not up for debate due to the formal and advanced planning process.

Conclusion

The case studies in Vienna and Lucerne reveal that using AR not only increases inhabitants' motivation to participate in planning processes but can also contribute to improving the quality of participation processes. The AR applications in Vienna and Lucerne present the planning intentions in a more realistic manner, as the concrete projects (planting of trees, creation of a cycling connection, installation of benches, etc.) are displayed in front of the actual existing background appearance. However, the extent to which AR-based visualizations – with their high level of detail, simulations, etc. – are actually better suited for participation processes than 2D plans (e.g., in the form of increased participation, more intensive discussions) was not directly analyzed in the two case studies and has not been addressed in the subsequent surveys by the project partners in Vienna and Lucerne. Nevertheless, experiences from other studies and research projects suggest that AR applications can significantly improve the quality of the participation process (see above research design).

AR applications can also be used in different planning phases. In Vienna, AR was used at the very beginning of the planning process. By presenting scenarios and options for action via AR, the intention here was to raise awareness for planning actions that might help to improve the microclimate. Here, AR is particularly beneficial as various, and occasionally conflicting, alternatives and solutions can be discussed and compared. In Lucerne, AR was used at the end of the planning process. Here, the city of Lucerne used an AR application to present the selected planning option on site (including the intended design of the public space); however, there was no discussion of the planning alternative in the AR application. Other studies and research >

projects (see research design above) similarly indicate that AR is mainly used in specific planning phases – primarily in advanced stages in the planning process – in order to visualize and, if necessary, objectify issues. Thus, the potential of AR applications in planning may not fully be exploited; therefore, in the future, the aim should be to use AR across all planning phases to visualize possible implications of individual projects in early planning phases and to make the discussion on planning alternatives more interactive and transparent.

Further, the case studies in Vienna and Lucerne and Vienna reveal that the different forms of visualization in the AR applications in Vienna and Lucerne contributed to making planning more tangible for participants. The experiences indicate that the use of AR applications, compared to analog participation formats and 2-D representations, helps to prepare the planning information for all interested parties in a visual and descriptive manner. Simultaneously, it makes the planning options more transparent, thereby implying that the AR application makes discussions among planners, politicians, citizens, and other stakeholders more objective. The Lucerne case study has shown that AR can also motivate groups that have been thus far underrepresented to participate in planning processes. However, the experiences in Vienna also indicate that the acceptance of AR as a visualization and participation tool has, thus far, been rather low compared to analog participation formats. Additionally, it was evident that AR as a digital participatory tool is not available to all users and, thus, there may be differences in accessibility and usage. Here, it must be ensured that participation processes based on AR do not lead to a manifestation of social inequalities. The combination of analog and digital participation tools may make sense here, but reliable results on this are not yet available. In any case, further research is needed in this respect, as the surveys conducted thus far tend to refer to user satisfaction with the AR application; the quality of the visualizations or the incorporating of the results in the further planning process has not yet been researched.

Nevertheless, AR applications can help ensure that sustainable development goals are given more importance in planning processes by, for example, displaying simulations relevant to urban sustainable transitions and testing scenarios or fostering interactive decision-support systems (Potts 2020, 283). This is rather evident in Vienna, where the AR application depicts the consequences of climate change for the urban neighborhood and, simultaneously, allows the selection of specific planning options (particularly planting measures) to learn how these options might improve the microclimate. By doing so, the AR application contributes to a sustainable planning process and, consequently, to sustainable urban development, because planning contents are presented in a real and transparent manner before actual construction measures begin.

In addition, AR applications also offer the potential to be linked with artificial intelligence (AI) systems.[4] New technical solutions in computer graphics, data mining and visualization, and visual and statistical analyses (Kitchin 2022, pp. 100 f.) enable urban planners and decision-makers "to tie these visual tools in with much more detailed, longitudinal, massive performance data sets to support comprehensive and useful forms of visual analytics" (Lock et al. 2019). For example, with regard to climate mitigation and adaptation, a digital twin (Dembski et al. 2020, Ruohomäki et al. 2018) could represent the digital (cross-sectional) infrastructure of the climate-neutral city and also integrate georeferenced data, real-time data (e.g., traffic flows, energy consumption), etc. On this basis, AR can be used to develop "what happens if ..." scenarios to illustrate, for example, the impact or effectiveness of individual options (e.g., shifts in traffic flows, energy savings in the neighborhood) with regard to climate protection or adaptation goals. In this vein, digital twins (as part of AI) and AR can together contribute to facilitating coordination of climate mitigation and adaptation options of different municipal departments. Simultaneously, they can analyze and evaluate sustainable and less sustainable development options throughout the entire planning process (from the development of alternatives to the concretization of partial solutions to design issues at the building level). Additionally, they can contribute to increasing the transparency and acceptance of climate mitigation and adaptation options among private actors and to improve the decision-making basis for politicians and planners. However, further empirical research and studies must be conducted in this regard, as all AR applications thus far have been developed and tested in research projects with a limited duration, thereby implying that they have not been actualized in a comprehensive, longer-term manner.

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4 For a reflection on the potential of data from smart city approaches in sustainability research see Koch et al. (2023, in this issue).

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More sustainable artificial intelligence systems through stakeholder involvement?

Artificial intelligence (AI) systems carry risks and opportunities for environmental sustainability. The use of AI systems, for instance, can result in both software-related (direct) as well as application-context-related (indirect) resource use. Stakeholders are expected to play a role in understanding and steering the environmental effects of AI systems. However, the processes and anticipated outcomes of stakeholder involvement in AI system lifecycles are not clear. We provide a non-exhaustive scoping review of six software and AI sustainability frameworks with respect to their recognition of environmental sustainability and the role of stakeholders in dealing with environmental sustainability. This serves to develop recommendations for future research on how stakeholder involvement can help firms and institutions design and use more sustainable AI systems.

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More sustainable artificial intelligence systems through stakeholder involvement? | *GAIA* 32/S1 (2023): 64–70
Keywords: artificial intelligence (AI), environmental effects, environmental sustainability, machine learning, software sustainability, stakeholder involvement, sustainable artificial intelligence (AI)

While social issues around artificial intelligence (AI) systems (such as the explainability and fairness of AI systems) have been the focus of much public debate, the environmental dimension of sustainability of AI systems has received less attention (Perucica and Andjelkovic 2022). AI development and use, for instance, require energy and cause high emissions (direct environmental effect) (Dodge et al. 2022). Moreover, the broader environmental effects of using AI systems in other fields of society (indirect environmental effect), such as increased consumption induced by AI-aided marketing, can cause substantial negative sustainability impacts. Irrespective of these risks, AI could be used for purposes beneficial for sustainability, for example, to gather and assess information about environmental issues (Nishant et al. 2020).

To counter negative and promote positive effects of AI systems, there is increasing interest in stakeholders' role to build more (environmentally) sustainable AI systems (OECD 2022, UNESCO 2022). Stakeholders in the context of AI systems may be clients who order an AI system, software firms, private users and governmental institutions who regulate AI systems, among others. The European Commission states that "the broader society, other sentient beings and the environment should be [...] considered as stakeholders throughout the AI system's lifecycle. Sustainability and ecological responsibility of AI systems should be encouraged" (HLEG AI 2019 b, p. 19). When calls for the recognition of stakeholders are made, however, it often remains unclear who stakeholders are in the context of environmental sustainability and what specific requirements environmentally sustainable AI should adhere to (Perucica and Andjelkovic 2022).

In this *Forum* article, we ask whether and how the involvement of stakeholders as one key characteristic of transdisciplinary research (Lawrence et al. 2022) is able to enhance our understanding of and dealing with AI systems' environmental effects. To discuss this question, we perform a scoping review of six software and AI sustainability frameworks. First, we analyse four sustainability frameworks for software more broadly and two sustainability frameworks for AI in particular regarding the environmental effects of software/AI they recognise and the extent to which they incorporate stakeholder involvement as a tool to identify and mitigate environmental effects in software/AI lifecycles. The analysis of both software (of which AI is part) and AI sustainability frameworks serves to increase the pool of knowledge of the environmental sustainability effects of AI and how to address them. Second, we discuss to what extent the (stronger) involvement of stakeholders could help address the weaknesses and foster the strengths of these frameworks applied to AI. Finally, we suggest future research directions regarding stakeholder involvement and multi-dimensional sustainability considerations for AI as well as software more broadly.

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Environmental effects of artificial intelligence

Artificial intelligence and environmental sustainability

The High-Level Expert Group on Artificial Intelligence set up by the European Commission defines AI systems as "software systems (and possibly also hardware) systems designed by humans that, given a complex goal, act in the physical or digital dimension by perceiving their environment through data acquisition, interpreting the collected structured or unstructured data, reasoning on the knowledge, or processing the information, derived from this data and deciding the best action(s) to take to achieve the given goal" (HLEG AI 2019a, p. 6). Following concepts of human intelligence, typical goals for AI include understanding language, vision and problem solving. There are numerous AI techniques which build on different concepts and algorithms, such as machine learning or natural language processing. They are frequently used in search engines, image recognition software or modern robotics applications (Döbel et al. 2018).

AI systems are usually embedded in broader software systems and come with particularities that differ from "traditional" software. For the present context, the following particularities are deemed important: firstly, AI systems are more data-driven than other software. Data is fed into the system not only during its use but particularly during its initial development. Thus, experimentation with training data is at the core of AI development rather than written code (Wan et al. 2020). Secondly, AI is able to automatically evolve during the use phase, whereas other software gets updated manually. In fraud detection, for instance, a machine learning system is expected to adapt to entities that try to outplay the algorithm by reiterating the learning algorithm with the new data or train an entirely new machine learning model (Wan et al. 2020). This may lead to "unexpected" outcomes in learning processes.

Drawing from literature on software sustainability effects, we distinguish two types of environmental effects of AI: direct and indirect environmental effects (figure 1).

Direct environmental effects

Direct environmental effects are considered all those environmental effects that occur along the lifecycle of an AI system itself, that is, environmental effects due to the production, use and disposal of physical hardware, infrastructure and software (Hilty et al. 2006, Bieser and Hilty 2018). As AI architectures differ from other algorithmic software (Gailhofer et al. 2021), AI systems' negative direct environmental effects may be larger than for other software. Patterson et al. (2021) show, for example, that emissions in training an AI system can increase more than a hundredfold depending on the architecture, processor types, data centres and power supply used. A positive direct environmental effect can arise if the AI system replaces a more energy- and resource-consuming software system (substitution effect; Börjesson Rivera et al. 2014).

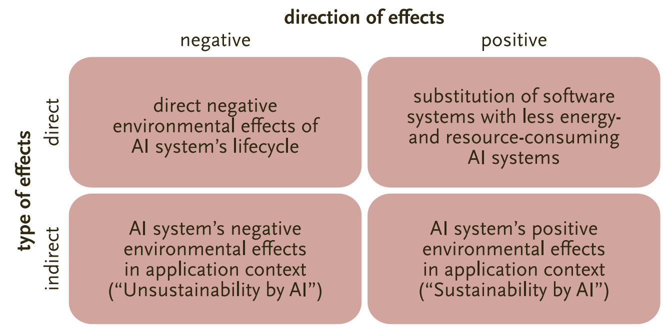

FIGURE 1: Categorisation of environmental effects of artificial intelligence (AI) systems. In this figure, the term "sustainability" refers to its environmental dimension.

Indirect environmental effects

Indirect environmental effects result from the application of systems in households, industry and agriculture, among others, which can affect the environmental sustainability of products and processes (Bieser and Hilty 2018, Börjesson Rivera et al. 2014). Increasingly automated production processes in firms, for instance, might affect their process and energy efficiency. On the one hand, AI systems entail negative indirect environmental effects. These can arise in the form of rematerialisation, induction, substitution or rebound effects, among others (Börjesson Rivera et al. 2014, Willenbacher et al. 2021) and may only become evident at the societal level and/or long term. For example, the use of individualised advertising is targeted at increasing the consumption of goods and services (induction effect) with a likely negative impact on environmental sustainability.[1] Likewise, intelligent mobility planning can make individual transport so attractive that it increases the rate of mobility and renders public transport less attractive (rebound and substitution effect, what we call "Unsustainability by AI"). With a view to positive indirect environmental effects, AI systems are supposed to contribute to sustainability in their application ("AI for sustainability" or what we call "Sustainability by AI"). For instance, AI systems are supposed to enable a flexible management of decentralised energy systems, which are confronted with fluctuations in renewable energy supply and demand (Antonopoulos et al. 2020).

Figure 1 summarises our categorisation of environmental effects (direct and indirect) and their directions (positive and negative).

Measuring environmental sustainability of artificial intelligence

An increasing body of literature deals with the question of how to measure direct and indirect environmental effects of AI (OECD 2022). For direct environmental effects of AI, different tools to measure the (direct) carbon footprint of AI are available (see table A in the online supplement[2]), but challenges in the >

1 See Gossen and Lell (2023, in this issue) for consumer policies initiatives tackling such environmental effects of digitalization.

2 See the online supplement *https://doi.org/10.14512/gaia.32.S1.10.suppl*.

measurement remain (Dodge et al. 2022). Carbon footprint is only one aspect of environmental sustainability. Measuring the entire embodied environmental footprint of the hardware used for computing, for instance, requires information on complex supply chains for electronics components regarding waste, chemicals use and biodiversity impacts, among others – but measurement of such environmental data is currently limited (Kunkel et al. 2022). For indirect effects, identifying and quantifying these effects is challenging, as questions about causality and system boundaries need to be addressed: to what extent is the use of a specific AI system causally responsible for an indirect environmental effect in society at large? What would have been the counterfactual outcome had an alternative (software) system been used? With the increasing call for stakeholder involvement in AI development, the question arises whether the involvement of stakeholders can contribute to overcoming some of these challenges and help identify, measure and mitigate direct and indirect environmental effects of AI systems. And if so, how?

Stakeholder involvement in artificial intelligence and software sustainability frameworks

To study the role of stakeholder involvement, we conducted a scoping review of a set of AI and software sustainability frameworks[3] regarding

1. which environmental effects they recognise and
2. to what extent they incorporate stakeholder involvement as a tool to identify and mitigate environmental effects in software/AI lifecycles.

Our main intention for the selection of frameworks was to cover a certain diversity of approaches. We chose AI-specific (two frameworks) and general software-related frameworks (four frameworks) which cover either several dimensions of sustainability (three frameworks) or only the environmental dimension of sustainability (three frameworks). The frameworks are provided either by industry (Microsoft principles) or found in scientific literature (all others). However, our *list of frameworks is not a representative sample* but serves to illustrate existing linkages in AI and software sustainability framework literature with stakeholder involvement. For a systematic literature review of software sustainability frameworks, for instance, see Penzenstadler et al. (2012) and Venters et al. (2018).

We extracted information on environmental effects and stakeholder involvement from the frameworks according to our two research questions. We did not use a fixed set of keywords to delineate "environmental effects" and "stakeholder involvement"; therefore, our results are our interpretations of these frameworks. We would appreciate a debate with the authors of the frameworks on our arguments. Detailed results of the analysis can be found in table B in the online supplement[2].

To summarise the analysed frameworks, two general software frameworks consider multiple dimensions of sustainability. A framework for *incorporating sustainability design in the software engineering lifecycle* is applied by Saputri and Lee (2021) to a case study. The *Sustainability Awareness Framework* (Duboc et al. 2020, Penzenstadler et al. 2020) also focuses on requirements engineering for sustainability and proposes five sustainability dimensions for software systems: social, individual, environmental, economic and technical. The framework is operationalised in the form of a workshop workbook which we analyse (Penzenstadler et al. 2020). Two of the general software-related frameworks only address the environmental dimension of sustainability. The first framework, *Kriterienkatalog nachhaltige Software* (Eng.: sustainable software criteria catalogue) (Hilty et al. 2017), focuses on resource efficiency, duration of hardware use and use autonomy. The second one by Microsoft (2022), the *Principles of Sustainable Software Engineering,* describes eight sustainability principles for improving the carbon efficiency of software, and is disseminated in the form of an online course on sustainable software development for practitioners which we analyse. Regarding AI systems, *Nachhaltigkeitskriterien für künstliche Intelligenz* (Eng.: sustainability criteria for artificial intelligence) by Rohde et al. (2021) suggest 13 sustainability criteria for AI systems for several sustainability dimensions. In their article *Aligning artificial intelligence with climate change mitigation,* Kaack et al. (2022) focus on the environmental dimension of sustainability and propose addressing the greenhouse gas emissions of AI in three categories: computational impacts, direct application impacts, and system-level impacts.

Results: Artificial intelligence, software sustainability and stakeholder involvement

Can stakeholder involvement as one characteristic of transdisciplinary research enhance our understanding, measuring and mitigation of environmental effects of AI?

First, we examined the recognition of environmental effects in software and AI sustainability frameworks. The frameworks by Hilty et al. (2017) as well Microsoft (2022) treat in varying technical detail mainly direct environmental effects along the lifecycle of software, such as the resource efficiency and carbon footprint of hardware and the environmental effects of necessary infrastructure for software. The environmental sustainability definition in the two frameworks is similar, that is, achieving a certain functionality with the lowest possible resource use. Saputri and Lee (2021), Penzenstadler et al. (2020), Rohde et al. (2022) and Kaack et al. (2022) more explicitly consider indirect (environmental) effects in their sustainability definition. Saputri and Lee (2021), however, only make a generic suggestion on "using environmental risk mitigation and having maintenance

3 We use the term "frameworks" loosely to refer to different sustainability approaches suggested in the works included in our scoping review. These approaches comprise a workshop procedure, an online course, a case study and sets of sustainability criteria stated in scientific publications.

guidelines" to address indirect environmental effects. Penzenstadler et al. (2020), in contrast, include specific questions on material and resources, soil, atmospheric and water pollution, energy, biodiversity, land use and logistics. Rohde et al. (2022) and Kaack et al. (2022) treat the positive and negative sustainability potential of AI for production and consumption and its risk of creating rebounds. While Rohde et al. (2022) consider four sustainability criteria on ecological aspects (energy, emissions, indirect resource use and sustainability potentials), Kaack et al. (2022) limit their framework to global greenhouse gas emissions and thus do not provide guidance on other environmental factors.

Secondly, we examined the extent to which the analysed frameworks incorporate stakeholder involvement. Our analysis shows that the frameworks generally recommend some sort of involvement of (non-scientific) stakeholders. Hilty et al. (2017) as well as Microsoft (2022) mention aspects of stakeholder inclusion, for example, involving "examiners" for computing sustainability or involving users to enhance the uptake of more environmentally sustainable software solutions. The Microsoft principle "demand shaping" suggests influencing user behaviour towards less energy-consuming uses of software and thereby try not only to increase resource efficiency but also to reduce demand. Moreover, several of the Microsoft principles imply that other parts of the firm and possibly stakeholders other than the programmer herself/himself would need to be involved in making software sustainability-related decisions. Rohde et al. (2022) consider the identification, classification and inclusion of stakeholders important along the entire lifecycle of AI systems and regard the number of stakeholder workshops (organised by the developing or using organisation of AI) as one important metric to measure stakeholder involvement. However, open questions remain about the design of such an involvement process and the expected outcomes with regard to environmental sustainability (e.g., how the involvement can be operationalised at the firm level throughout the entire lifecycle and how the identified environmental sustainability requirements feed back into the lifecycle). In Kaack et al. (2022), stakeholder relevance is implicitly acknowledged, for example, when stating the concern that dual use of the same technology can lead to either harmful or beneficial effects on the environment. However, the authors do not specify how more environmentally beneficial uses of technologies can be ensured.

Saputri and Lee (2021) as well as Penzenstadler et al. (2020) describe the attempt to capture trade-offs in the assessment of various sustainability levels of software development through requirements engineering. Requirements engineering is an established way to involve stakeholders in software engineering and has been explored as an approach to software sustainability (Duboc et al. 2020, Penzenstadler 2014). In Saputri and Lee (2021), a multi-criteria matrix for various sustainability aspects is established, and stakeholder requirements are captured at the beginning of the design process. Stakeholders can prioritise different sustainability dimensions, leading to priority scores for each dimension. Engineers need to weigh different stakeholders' needs and develop software requirements. However, it remains unclear by whom and how exactly environmental risks are going to be identified and mitigated in requirements engineering.

Penzenstadler et al. (2020) take a more practical approach offering a workbook for practitioners to raise awareness of sustainability effects in software engineering. They suggest a process for stakeholder workshops, where requirements engineers and stakeholders elaborate requirements for software to represent stakeholders' needs. They acknowledge, however, that the primary goal of the workshop is to raise awareness and that a "comprehensive sustainability impact analysis requires further work". Applied to AI systems, additional challenges might arise in the suggested workshop. The requirements in machine learning systems, for instance, are rather data- than code-driven and depend more on particular application contexts. In other words, different data and application contexts lead to different requirements (Wan et al. 2020). Thus, the workshop might need to be repeated for each project in a firm, which leads to questions of practicability.

Even if artificial intelligence systems are designed to minimise their negative direct environmental effects, their main goal may still be to promote unsustainable production and consumption patterns.

Discussion and research directions for stakeholder involvement for sustainable artificial intelligence systems

With a call for broader stakeholder involvement for sustainable AI systems (UNESCO 2022), the question arises if and how such involvement helps enhancing the sustainability of AI systems and how it can be put in practice. In this article, we focused on the environmental dimension of sustainability and its links with stakeholder involvement. We conclude from our scoping review of AI and software sustainability frameworks that stakeholders seem to be expected to inform specific questions on environmental effects, since no one-stop-shop approach for measuring direct and indirect environmental effects of AI/software is avail- >

able. However, while stakeholder involvement is considered important at an abstract level, we conclude that the exact processes and aims (who, how, when, why) of stakeholder involvement are not explained in sufficient detail in the analysed frameworks. Moreover, links to environmental sustainability are sometimes not made explicit. Specifically, frameworks are not clear about who stakeholders are in the context of environmental effects and what types of knowledge they could contribute to assess and mitigate environmental effects of AI/software at what stage of the AI/software lifecycle. It could be a practical challenge for developers and institutions to integrate stakeholders even if they deemed this step important. Preliminary insights into the implementation deficit of "trustworthy" AI support this concern (Beckert 2021). Even if these challenges were overcome in some firms/institutions, there would still be questions of how and why sustainability frameworks would be used at scale, that is, what the incentives and expected (economic) benefits are for firms/institutions to develop and use sustainable AI. Notwithstanding these challenges, we believe that there are several ways in which stakeholder involvement can benefit the development of sustainable AI, and ways in which research could learn more about and foster stakeholder involvement.

Stakeholder involvement to identify and assess indirect environmental effects of artificial intelligence

Our scoping review suggests that while the technical details of software and hardware optimisation may be difficult to assess by (non-technical) stakeholders, stakeholder involvement could help unveil and assess less obvious indirect environmental effects, such as rebound effects in firms using AI systems, or behaviour changes on the side of consumers. Stakeholders may be in a position to shift the debate away from a narrow focus on how to make AI systems themselves more sustainable (direct environmental effects of AI systems) to the question of what these systems are used for and which indirect environmental effects, including outside the firm's value chain, this can have ("Sustainability by AI" and "Unsustainability by AI"; figure 1). For instance, if the AI system is designed according to environmental sustainability criteria minimising its negative direct environmental effects, its main purpose could still be to trigger additional consumption by addressing customers through targeted advertisement. This negative indirect environmental effect may be larger and thus more problematic than direct environmental effects.

Stakeholder involvement to define and evaluate trade-offs between and within different dimensions of sustainability

Developers might need support and societal legitimisation in decisions over trade-offs, for example, between different environmental aspects or between environmental and social aspects of AI development. It could be helpful to involve stakeholders in identifying and evaluating trade-offs. Questions such as "If I can only reduce either the hardware requirements of my AI system or address the issue of server energy use – what should I do (first)?" or "What is the interplay between privacy and environmental concerns in my system?" could be addressed. Again, the devil lies in the details, and several procedural questions will have to be clarified. Who exactly are stakeholders for each sustainability dimension (Penzenstadler 2014)? For instance, is there one advocate in the firm who can represent environmental interests in different environmental fields, such as biodiversity or land and water use? Would it be sufficient to involve sustainability stakeholders in the requirements engineering phase, or would a continued involvement be necessary? (When) Would external stakeholders, such as environmental organisations, be needed? How could stakeholders negotiate conflicts between different sustainability dimensions?

Stakeholder involvement to align agendas of industry, politics and civil society and bring existing frameworks into use

Stakeholder involvement can also be a concrete step towards finding common ground in the agendas of industry, politics and civil society and thereby contribute to uptake of existing sustainability frameworks in firms and institutions. For instance, multi-stakeholder processes involving international organisations, governments, civil society and the private sector are suggested to address the lack of comparable measurements of environmental effects of AI (OECD 2022, UNESCO 2022). Based on standardised measurements, AI developers and users can more easily start to measure AI-related environmental effects and start discussions on priorities regarding different aspects of sustainability. If industry stakeholders are involved, the likeliness that the developed measures will be relevant and taken up in industrial application contexts may increase. Regarding the suggested sustainability principle that hardware lifetime should be extended, for instance, its implementation would need both the buy-in of firms to foster long-lived products and policies to regulate repairability, minimum support and use times of hardware. Likewise, if users are supposed to use digital technology products longer, which information channels and incentives are there to foster this behaviour?

Some open questions around operationalising stakeholder involvement for (environmental) sustainability of artificial intelligence systems

A major limitation of this scoping study is that we did not do a systematic review of sustainability frameworks, so there might be relevant work that we have overlooked which provides some answers to our questions around stakeholder involvement for sustainable AI. Notwithstanding, given the current lack of awareness of sustainable software systems in practice (Karita et al. 2019), we believe that there is still a lot to learn on how to *do* sustainable software, AI and stakeholder involvement, and we hope to encourage further work at this nexus. Specifically, we suggest that future research should

- implement case studies on "sustainable AI" in firms/institutions, using existing sustainability frameworks for sustainable software/AI (such as in Porras et al. 2021 for software),

- gather data from case studies on
  - barriers to measuring and steering environmental effects of AI,
  - which stakeholders (can) contribute at what stage of the lifecycle of AI to bring environmental and other sustainability effects to the attention of developers, managers, politicians and users,
  - how different sustainability dimensions (social, economic, individual, technical, environmental) can be weighed and trade-offs be evaluated,
- (if needed) create more detailed guidelines and decision matrices to further operationalise stakeholder involvement in sustainability frameworks for firms/institutions, and
- understand barriers to and foster the uptake of sustainability frameworks in practice.

Large bodies of knowledge regarding (software) sustainability already exist which can bring relevant insights for the assessment of sustainability effects of AI, but they are spread across different disciplines and domains. This is where (inter- and) transdisciplinary research could likely make a large impact, by bridging the gap between scientific discussion and the need for practically relevant guidelines and advice.

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Sustainable consumption in the digital age

A plea for a systemic policy approach to turn risks into opportunities

Digitalization offers opportunities for sustainable consumption patterns. However, the patterns enforced by present digital business models are not sustainable. Current European Union regulatory approaches for both consumers and environmental policies do not systematically address this challenge. By introducing "positive accountability," we propose a systemic policy approach to hold digital companies accountable for their impact on consumers and the environment; supporting sustainable consumption in the digital age.

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Sustainable consumption in the digital age. A plea for a systemic policy approach to turn risks into opportunities
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The interplay of digitalization, sustainability, and consumption

Digitalization and sustainability are often referred to as two megatrends that are shaping the economy and society (Del Río Castro et al. 2021, BMU 2020). However, the two phenomena are very different: digitalization is massively changing reality and influencing almost every aspect of our lives, while sustainability is a normative goal that has not yet become a reality in most areas. We believe this is especially true in the area of sustainable consumption. We agree with other scholars that whether digitalization supports or threatens sustainable goals depends on how it is shaped by political and societal actors (Frick et al. 2021, Lange and Santarius 2020, Osburg and Lohrmann 2017, WBGU 2019). In the area of consumption, digitalization has the potential to support sustainable development by promoting reuse, repair, sharing, and the circular economy. Although these effects are already being observed to some extent (Gossen et al. 2022), we believe these positive trends are outweighed by unsustainable consumption patterns that are perpetuated and reinforced by digital business models (e. g., Lange and Santarius 2020).

The dominance of growth and profit in our economy and society is driving digitalization. This trend tends to have a negative impact on the environment, as it enables increases in effectiveness and productivity that translate into lower prices and consequently overproduction and overconsumption (Pfeiffer 2021). At the same time, digitalization has significantly changed the way market processes work: to gather data about individuals and the world around them, digital platforms employ the latest data analytics methods and computational capabilities with the goal of "to know, control, and modify behavior to produce new varieties of commodification, monetization, and control" (Zuboff 2015, p. 85). This "surveillance capitalism" (Zuboff 2015) has given unprecedented power to technology corporations, while tracking consumers' online behavior to personalize online content and increase revenue is likely to increase consumption (Kahlenborn et al. 2018, Kish 2020).

We believe that it is both possible and necessary to shape digitalization in ways that promote sustainable consumption. However, it seems that policy initiatives addressing digitalization and consumption have not yet achieved this. With this *Forum* article, we aim to contribute to a comprehensive, systemic policy approach to sustainable digitalization in the consumption sector. We do this in two steps. First, we provide illustrative examples of current policy approaches that are shaping the impact of digitalization on sustainable consumption. Second, we propose approaches for a systemic policy framework to promote sustainable consumption in the digital age.

Current policy agenda towards sustainable consumption in the digital age

Consumer policy approaches to digitalization

Ubiquitous data collection, unfair discrimination by algorithms, and the widespread use of so-called dark patterns threaten consumer privacy and undermine digital sovereignty. From a sustainable consumption perspective, these manipulations and privacy violations mean that online shopping overconsumption is encouraged (D4S 2022). A number of policy initiatives have been taken in the European Union (EU) to address these features of >

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digitalization. Below, we explain the regulatory approach underlying the most prominent policy initiatives from a consumer policy perspective.

Privacy policy

The *EU's General Data Protection Regulation (GDPR)* (Regulation [EU] 2016/679) is seen as a global milestone for privacy protection and has inspired other governments to take similar initiatives (Heine 2021). However, the *General Data Protection Regulation* has not yet curbed extensive data collection practices. While data protection authorities have been able to force digital companies to change certain aspects of their data-based business models, such as the conditions for obtaining consumer consent for data collection (CNIL 2022), the efforts required to enforce the *General Data Protection Regulation,* along with varying interpretations of its legal ambiguities, have led to "uneven and sometimes non-existent enforcement" (EP 2021, margin no. 12).

Consumer rights

The *Digital Services Act (DSA)* (Regulation [EU] 2022/2065) of 2022 represents a major change in the regulation of digital platforms. First, it establishes how digital platforms must behave in the market. It prohibits the manipulation of consumers through so-called dark patterns, targeted advertising aimed at children, and the use of sensitive data for targeted advertising. Second, the *Digital Services Act* holds platforms accountable for the systemic impact of their business models on society, including the erosion of consumer protection.

Algorithmic accountability

In response to the impact of artificial intelligence (AI) on issues such as autonomy, self-determination, and consumer privacy, the European Commission has put forward a new proposal for an EU legal framework for AI in 2021. If adopted, this *Artificial Intelligence Act (AIA)* (EC 2021) will take another step toward accountability for digital businesses. AI systems will be classified into different risk classes, subject to certain conditions ranging from a ban to compliance with mandatory regulations and transparency requirements. However, the risk assessment introduced by the proposed *Artificial Intelligence Act* is based only on the impact of AI systems at the level of individuals – especially in relation to issues such as discrimination or wrong decisions with negative consequences for an individual. It does not consider the impact of AI systems on society, including the impact on the environment, such as reinforcing unsustainable consumption patterns (Smuha 2021).

It is necessary that both consumer and environmental policy approaches shape digitalization in ways that promote sustainable consumption. However, it seems that policy initiatives addressing digitalization and consumption have not yet achieved this.

Environmental policy initiatives relevant to consumption in a digital world

Digital technologies pose a significant risk to sustainable consumption, as they contribute both directly and indirectly to the increase in energy and material consumption in the digital world. In addition, new options for digital consumption further increase energy and material demand, and digital marketing strategies such as personalized advertising stimulate consumption needs and encourage the purchase of new products (D4S 2022). In the EU, several initiatives under the *European Green Deal* address sustainable consumption as a cross-cutting issue. In the following, we explain the approach taken by environmental policy with regard to the impact of digitalization on sustainable consumption.

Circular economy and sustainable products

The *EU Circular Economy Action Plan (CEAP)* aims to make almost all material goods in the EU market more environmentally friendly, circular and energy efficient throughout their life cycle, and to empower consumers for the green transition. As part of the *Circular Economy Action Plan,* the *Sustainable Products Initiative (SPI*) has proposed a regulation on ecodesign for sustainable products (EC 2022) that establishes a framework for ecodesign requirements for specific product groups. It builds on the existing *Ecodesign Directive* (Directive 2009/125/EC) (which currently covers only energy-related products) and targets almost all categories of physical goods. The legislation will ensure that consumers have a sustainable choice of products on the EU market.

Digitalization as a tool for environmental policy

The *Circular Economy Action Plan* aims to use digitalization as a means to promote sustainable consumption. To this end, Digital Product Passports will be developed to help consumers and businesses make informed choices when purchasing products, facilitate repairs and recycling, and improve transparency about the environmental impact of a product's lifecycle (Pietron et al. 2023, in this issue). In addition to consumer policies aimed at combating misinformation, the *Green Claims Initiative* will require companies to substantiate their claims about the environmental footprint of their products or services by quantifying them using standard methods. The aim is to make claims reliable, comparable and verifiable across the EU, thereby curbing greenwashing. As a result, the Dutch Consumer Markets Authority has taken direct action by warning certain online retailers for making misleading marketing claims (Deeley 2022).

At the national level, Germany's *Digital Policy Agenda for the Environment* aims to put digitalization at the service of the environment, climate and nature, and to promote sustainable lifestyles through the use of digital solutions and the alignment of digital markets with sustainability requirements (BMU 2020). The agenda specifically addresses the incentives created by current digital business models to consume more instead of consuming sustainably. In order to steer consumers towards sustainable consumption, the agenda obliges platforms to inform consumers about their sustainability credentials and to include sustainability criteria in their recommendation algorithms.

An interim balance of current policy approaches to digitalization from a sustainable consumption perspective

Summarizing regulatory approaches, we find that specific policies for the digital economy are increasingly emerging in the consumer sector. Step by step, digital companies are being held accountable for certain harms and risks caused by prevailing business models. However, the impact of consumer policy on sustainable consumption remains limited. The goal of consumer policy is to protect individuals from the negative effects of digitalization, for example, manipulation, discrimination or economic disadvantages. Consumer legislation in the digital sector can therefore indirectly support sustainable consumption, for example by taking action against manipulative and privacy-invasive business models. However, promoting sustainable consumption is not the explicit goal of current consumer policies.

As far as environmental policy is concerned, we mainly see various efforts to use the potential of digitalization to promote both a circular economy and information on sustainability for consumers. However, the impact of digitalization on (unsustainable) consumer behavior remains largely unaddressed by environmental policy. In the platform economy, digital business models that are financially dependent on advertising reinforce unsustainable production and consumption patterns and exacerbate related environmental problems (Ramesohl et al. 2022, Gossen et al. 2022). Although environmental policies such as the *German Digital Agenda for the Environment* have begun to address these challenges, no policy approach has emerged that offers viable solutions. The role of digital platforms in particular, in promoting or preventing sustainable consumption patterns remains the "blind spot of platform regulation" (Ramesohl et al. 2022, p. 24).

A systemic policy approach for sustainable consumption in a digital world

Current digital strategy documents state that digitalization should serve the EU's goals and values, that is, promoting "a human-centered, inclusive, secure and open digital environment where digital technologies and services respect and enhance Union principles and values" (Decision [EU] 2022/2481, Art. 3[1][a]). However, as far as sustainable consumption is concerned, we note that we lack the tools to achieve this goal. We therefore argue that the European regulatory approach to digitalization should be completely rethought. Until now, policymakers and law enforcement agencies have been able to claim and prove damages and harms caused by digital business models. This regulatory logic should be reversed: because dominant digital platforms have massive impacts on society, consumers, and the environment, they should be held accountable for ensuring that these impacts are positive. This is an approach that is well established in other sectors of the economy. Infrastructure operators in services of general interest, such as electricity, water, or health services, are subject to extensive regulation to ensure that this infrastructure benefits society. This regulatory approach can also be applied to digital platforms, as they represent the informational infrastructure of society in the digital age (Busch 2021). Consequently, digital companies should on the one hand be required to discontinue business models that have obvious negative consequences for consumers and society, and on the other hand they should be held accountable for continuously improving their impact on consumers and society.

Putting an end to ubiquitous surveillance

The most salient and pressing issue to address when considering the negative consequences of digital business models is the manipulation system that has evolved through online advertising. In 2021, $455.30 billion will be spent on digital advertising, or 61% of total media advertising spend (Insider Intelligence 2021), resulting in commercial messages being ubiquitous and the average citizen being highly exposed to advertising on a daily basis. Moreover, not only the quantity but also the quality of advertising has changed. Efforts to increase the effectiveness of advertising in triggering purchases are diverse and include search engine optimization (SEO), personalization, big data, and machine learning. Studies show that personalized advertising drives impulsive buying behavior (Zafar et al. 2021) and that influencer campaigns can stimulate purchase intentions (Jiménez-Castillo and Sánchez-Fernández 2019).

Because dominant digital platforms have massive impacts on society, consumers, and the environment, they should be held accountable for ensuring that these impacts are positive.

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There are increasing calls to place limits on the collection, evaluation, and analysis of personal data that go beyond the standards of the *General Data Protection Regulation,* which can easily be undermined by consent. During the negotiations on the *Digital Services Act,* a group of members of the European Parliament advocated a ban on tracking-based advertising (Tracking-free Ads Coalition 2021). Although these voices are not reflected in the final compromise, we are convinced that the idea will remain relevant. In addition, strict limits could be placed on the use of personal data. For example, data could only be used to provide a specific service, and disclosure to third parties would be prohibited (Bennett et al. 2021).

Currently, calls to restrict or ban tracking and collection of personal data are motivated by consumer and privacy concerns. Yet these calls have a strong link to environmental policy, as they would not only increase consumer autonomy but also reduce unsustainable consumption patterns. The motivation for tracking consumers is to promote consumption and increase revenue for advertisers and retailers. Thus, if consumers are not tracked, additional consumption will be limited. This will promote digital business models oriented toward the common good and sustainability, which are currently limited to niche markets (Gossen et al. 2022).

Establishing positive accountability for the impact of digital platforms on consumers and society

Setting clear limits to digital business models that have significant negative impacts on consumers and the environment is essential to promoting sustainable consumption in the digital world, but it is not enough. Personalized advertising is just the tip of the iceberg in current digital business models. In Germany, for example, 34 % of the time consumers spend online is spent on websites and apps from *Facebook* and Alphabet, the parent company of *Google* and *YouTube* (Andree and Thomsen 2020, p. 38). These two companies allocate 45 % of subsequent internet activity to other websites or apps (Andree and Thomsen 2020, p. 38). This highlights the strong influence these platforms have on consumer behavior – and when you consider that both platforms rely on advertising as a source of revenue, it becomes clear how great their potential is to drive consumption.

To some extent, digital platforms are already held accountable for the impact of their business models on society through the *Digital Services Act* and the proposed *Artificial Intelligence Act.* We believe that this accountability should no longer be enforced only negatively through prohibitions on manipulation, invasion of privacy, or discrimination. Rather, platforms should be held accountable (and rewarded) for continuously improving their impact on consumers and society. For the impact of digital platforms on consumption, this means that platforms should allow independent researchers access to their data so that these impacts can be explored in detail – as well as the impact of digital platforms on society, for example through fake news and hate speech. Based on these findings, ways should be sought to turn negative impacts into positive ones. One important aspect will be to develop alternatives to advertising-based digital business models (Bennett et al. 2021), possibly based on micropayments for content use (Lanier 2014). Similarly, the impact of search, recommendation, and transaction processes on consumers should be monitored, and these processes should be designed to meet consumers' interests and promote sustainable consumption. The largest online platforms should build a neutral choice architecture that enables consumers to make the same choices they would make if they had the time, information, and incentives necessary to make careful and deliberate choices (Fletcher et al. 2021).

How can we achieve such strong accountability in digital policy? The procedural approach for doing so has already been established: the Institute of Electrical and Electronics Engineers (IEEE), a technology standards organization, has issued *IEEE Standard 7000TM-2021* on "integrating ethical and functional requirements to mitigate risk and increase innovation in systems engineering" (IEEE 2021). To determine the impact of IT systems on values in a given situation, one of the requirements of the standard is extensive stakeholder participation (Spiekermann 2021).

However, aligning digital business models with consumer interests and the goal of sustainable consumption is obviously not in line with the interests of the dominant digital platforms. Therefore, positive accountability of digital platforms should be anchored in the regulatory system. Models for this exist in other areas of regulation: for decades, environmental law has required industry to continuously improve the environmental performance of its products and industries. In the same vein, technology companies should be required to continuously improve their business models to promote both consumer interests and sustainable consumption.

Making this a legal requirement might be less demanding than expected: in consumer law, for example, the necessary shift could be achieved simply by reversing the burden of proof. Digital companies with market power would have to prove that user guidance and recommendation systems are not manipulative in the service of platform interests, but are aligned with consumer interests (Helberger et al. 2021, Fletcher et al. 2021). To meet this burden of proof, they would need to rely on standards for value-based engineering, such as the *IEEE 7000TM-2021* mentioned above.

Outlook

The regulatory rethinking we call for is profound. Further research, social dialogue, and policy agenda setting will be necessary to make it a reality.

What may make the "positive accountability" approach attractive from a regulatory perspective is that it is a natural alternative to the current approach of "siloed" regulation, where specific concerns are addressed through specific rules. The disadvantages of such specific obligations are obvious, as they invite workarounds and unintentionally disadvantage smaller players (Friederici and Graefe 2021). The "positive accountability" approach would lead to a comprehensive assessment of digital business models and introduce an integrated regulatory approach.

At the same time, it is important to note a limitation of the "positive accountability" approach. This arises from its basis in the synergies between consumer and environmental regulatory goals. If consumers support the idea of sustainable consumption, digital platforms will find many ways to address their needs and interests – by reducing commercial messages in general, favoring sustainable consumption alternatives in searches, and developing recommendations and sustainable shopping assistants. But there will also be situations where there are conflicts between consumer interests and environmental policy goals, especially if we consider that current consumption levels in industrialized nations far exceed planetary boundaries.

Such conflicts between consumer interests cannot be resolved by holding only digital corporations accountable for the environmental impacts of their IT systems and business models.

Rather, it is necessary to set political limits on consumption-driven resource use – just as there is political agreement on reducing climate gas emissions. Digital platforms will need to adapt their algorithms and business models to these limits, and digital accountability will need to be integrated into an even broader sustainable consumption strategy.

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