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Sustainability powered by digitalization? (Re-)politicizing the debate

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ABSTRACT
As ecological crises escalate, various stakeholders frame digitalization as a key solution for sustainability transformations. Besides incremental optimization, this promise has not materialized yet. We argue that digital solutions toward sustainability objectives are shaped by and reinforce power structures that effectively undermine sustainability outcomes. Academic discourse and governance are often dominated by a technology-centric framing in contrast to technologically informed, power-centric approaches. In this article, we develop an interdisciplinary framework to analyze three interconnected dimensions of power at the sustainability-digitalization-nexus and reveal how they obstruct sustainability. We locate power at the levels of environmental knowledge, governance, and technological materiality. First, digital technologies create representations of the environment that reinforce, reconfigure, or clash with preexisting ones, striving for more and better digital real-time data for technological control. Second, the spread of digital technologies is facilitated by emerging actor coalitions that promote digitalization while employing a reductionist understanding of sustainability. This narrows the policy space to optimization and incremental solutionism, which reproduces the status quo. Finally, the designs and material infrastructures of current digital technologies create path dependencies and lock-in effects while the underlying colonial resource and wealth flows remain hidden. We advocate for a (re-)politicization of digitalization across these dimensions to leverage its potential for sustainability transformations. We conclude that digitalization cannot spare us from political conflicts and deliberation processes about desirable sustainability futures. The debate should re-center fundamental questions about what kind of sustainable futures we want, where technology has a role to play, and where it does not.

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Introduction

In the face of escalating ecological crises, governments, businesses, and other stakeholders often present digitalization as a promising solution for achieving sustainability transformations. Research has pointed to applications in virtually all sectors that are supposed to enable more efficient use of resources and energy. In line with this work, public and private sector actors are making massive investments in digital technologies. However, beyond individual optimizing solutions, digitalization has hitherto failed to contribute to broader sustainability transformations (see, e.g., Bergman and Foxon 2023; Creutzig, Acemoglu, and Bai 2022; Freitag et al. 2021; Lange, Pohl, and Santarius 2020; WBGU 2019).

To understand and escape the impasse of digitalization for sustainability, this article examines the current discursive and material constitution of the sustainability-digitalization-nexus. We conceptualize this nexus as the overlap of two highly influential political projects, digitalization and sustainability, and their respective hegemonic discourses. On the ideational level, the equivalence between digital and sustainability objectives is constantly crafted, reinterpreted, and reworked (e.g., Kloppenburg et al. 2022; Kovacic et al. 2024; Nost and Colven 2022). Influential narratives such as the "twin transition" are pushed by new actor coalitions, including multinational technology companies. Dominant interpretive patterns of the role of digitalization for sustainability purposes are mirrored, resisted, or reshaped in the design of digital

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technology. We suggest that the potential of digitalization for sustainability transformations is not primarily a matter of technological innovation, but of power relations that manifest in discursive, institutional, and material dimensions. The conjunction of digitalization and sustainability is contingent and can be re-worked through different modes of contestation. The research questions of this article are: How do dominant power relations shape the digitalization-sustainability nexus? And how could this nexus potentially be reshaped toward sustainability?

Digitalization is understood as a process of increasing quantification, datafication, and automation via networked digital applications, reshaping social interactions, practices, actors, and infrastructures to the degree that it creates societal implications for politics, culture, economy, and so forth (Coy et al. 1992; Floyd, Fuchs, and Hofkirchner 2002; Floyd et al. 1992; UNGIS 2025). *Sustainability* is understood as the societal goal to provide a good life for all, today and in the future, and within the boundaries of the planet. It is commonly conceptualized in three dimensions (or pillars): the environmental, the economic, and the social (Purvis, Mao, and Robinson 2019; Rockström, Steffen, and Noone 2009). In this article, we particularly focus on efforts made to achieve environmental sustainability and sustainability transformations. We use the term transformation here in contrast to notions of sustainability transitions that often imply a linear progression of (ecological) modernization based on advancements in science and technology, coupled with effective governance instruments (Geels 2010; Loorbach and Rotmans 2010; Stirling 2011). Instead, we follow scholars like Ingolfur Blühdorn (2022) and Ulrich Brand (2016), who argue that these incremental and techno-centric reforms are inadequate for addressing the complex and intertwined ecological, social, and economic issues we face today. Genuine transformations require a radical rethinking of our norms, institutions, and unsustainable ways of living (Andreotti et al. 2015; Nightingale, Eriksen, and Taylor 2020). Transformations thus refer to structural changes of the social and political order in response to existential environmental crises.

It has become commonplace in the academic literature to argue that technology is never "neutral" but is embedded in power relations and, in turn, reinforces them (Feenberg, Felt, and Fouché 2017; Winner 1980). However, it is an open question how digitalization is reconfiguring prevailing approaches toward sustainability and how the sustainability discourse is disrupting or reinforcing the expansion of the digital. Research on the emerging nexus between technology and sustainability has been eclectic and subject to disciplinary divides, with contributions stemming from computer science, political ecology, governance scholarship, and science and technology studies, among others (e.g., Del Río Castro, González Fernández, and Uruburu Colsa 2021; Rolnick, Donti, and Kaack 2023; Vinuesa et al. 2020). However, the dimension of power is usually only of marginal importance in this literature and the contributions that deal with the role of power in digitalization processes for sustainability merely focus on single aspects such as power in relation to the material and energy footprint (e.g., Dauvergne 2021) or forms of knowing (Bakker 2022, 2024).

This article advances the literature by integrating interdisciplinary perspectives into a structured framework that systematically examines how different dimensions of power shape the sustainability-digitalization nexus across three spheres of contestation (see Figure 1). We draw together poststructuralist perspectives, the sustainability governance literature, critical computer science, and related disciplines to show how power underpins (1) the reconfiguration of environmental knowledge through digitalization, (2) the governance of digitalization for sustainability transformations, and (3) the materiality and (political) shape-ability of digital technology. These dimensions are codependent and mutually reinforcing. We argue that both the failure to leverage digitalization for sustainability transformations and the simultaneous push to advance digital solutions for sustainability objectives are deeply rooted in, and co-produced by, power structures that manifest in these distinct but interconnected spheres of contestation. Without a radical change in the conditions of the social and political context, digitalization will likely continue reproducing unsustainable patterns of natural resource exploitation and data extractivism.

These spheres of contestation are discussed in depth in the following sections. For each sphere of contestation, we operationalize a different approach toward power and corresponding potential for repoliticization. In the next section, we draw upon a Foucauldian understanding of power-knowledge to illustrate how *knowledge* and *discourse* at the sustainability-digitalization nexus reproduce dominant neoliberal rationalities and narrow the solution space for environmental sustainability. Building upon an institutional conception of power that highlights the tension between structure and agency, the third section turns toward the *governance and actor constellations* at the sustainability-digitalization nexus. In the fourth section, we analyze power as the ability to influence the purpose and shape of technical systems as informational algorithmic processing infrastructures

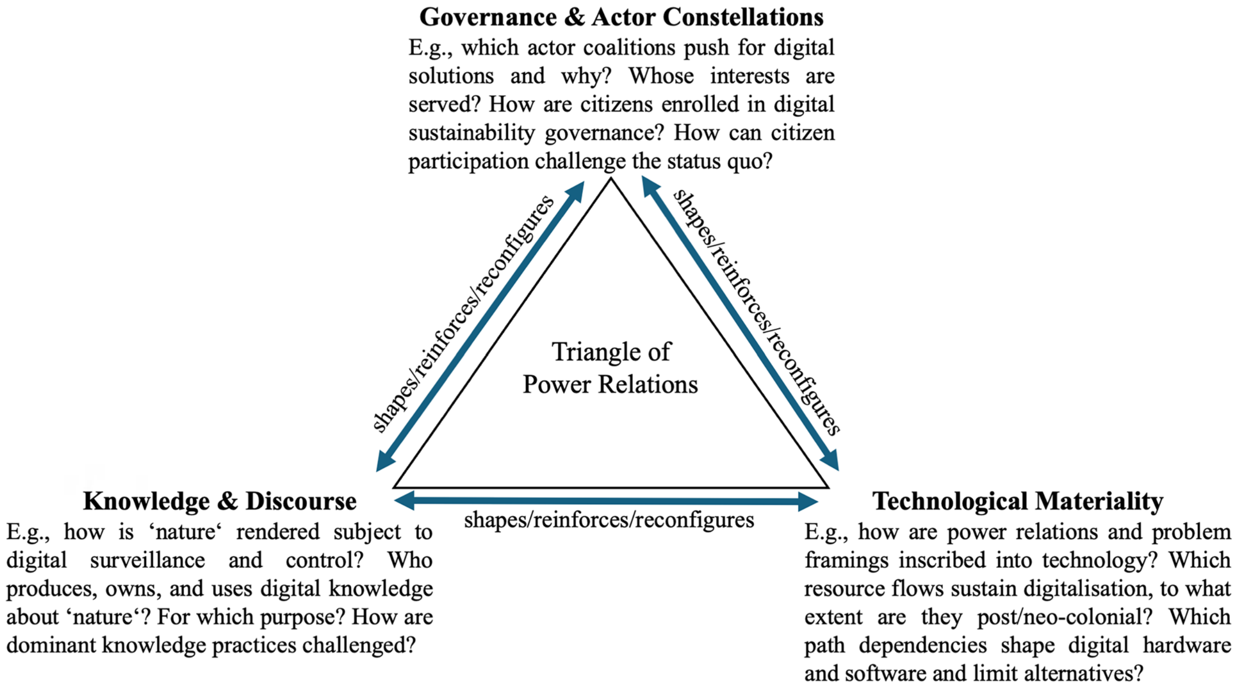

Figure 1. A new framework for understanding power relations at the sustainability-digitalization-nexus, based on three dimensions of power.

and physical computation-transmission infrastructures. Using this conception, we trace how power is inscribed and reproduced by the *technological materiality* of digital applications.

In our concluding discussion, we summarize our findings, advocate for the repoliticization of sustainability discourses, governance, and technologies, and provide directions for future research. To unleash the potential of digitalization for sustainability transformations, we need to overcome existing power structures and paradigms, including "the realities of material and social-political infrastructures that support the status quo" (Nightingale, Eriksen, and Taylor 2020, 343). With this analysis, we call into question depoliticized and over-optimistic narratives of digital sustainability transformations. While digital tools can be utilized for some tasks (see, e.g., Alli et al. 2023; Himeur et al. 2021; Santarius and Wagner 2023; Wilson, Paschen, and Pitt 2022), they do not provide answers to longstanding debates and deep-rooted societal conflicts in sustainability transformations. We suggest refocusing fundamental discussions about why, what, and for whom digital tools are mobilized, and whether/to what extent digitalization has any relevance at all for addressing current ecological crises.

Knowledge and discourse at the sustainability-digitalization nexus

The digital is not merely a means to an end but has evolved as a structuring element of sustainability discourses, co-producing sustainability futures (Ascui, Haward, and Lovell 2018) – similar to analogue statistics and modeling before the age of the computer (Scott 1998). Digitalization materializes through screens, smartphones, sea cables, drones, sensors, data centers, satellites, and more. It reconfigures how scientists, citizens, and policymakers relate to the environment and thereby potentially consolidates, challenges, or reworks existing power relations and rationalities of sustainability governance (see Brodie 2023; Gale, Ascui, and Lovell 2017). This section adopts a poststructuralist view of power as relational and productive (Foucault 1978). Following Michel Foucault, power is located in discourses and related practices that compete for hegemony/dominance (Foucault 1971). A discourse is defined as an intersubjective system of meaning that creates certain visibilities and imposes legitimate ways of thinking and acting on the physical world. Discourses allocate legitimate subject positions to actors, rendering some powerful while actively marginalizing others. When marginalized actors and discourses challenge the dominant discourse, an issue can become politicized.

According to Mitchell Dean's (2009) poststructuralist analytics of government framework, each historical configuration of government has its own ways of seeing, knowing, and governing. Using this framework, the following subsections explore the dominant ways of knowing, new visibilities, reconfigured identities, and changing technologies of government that are shaping the solution space for governing the sustainability-digitalization nexus.

New modes of knowing

As political ecologists point out, environmental data are "not so much collected but made" (Goldstein and Nost 2022, 5; also see more general Kitchin 2014). Environmental data are actively generated through socio-material infrastructures for specific purposes, constituting power-knowledge. For the case of climate change, Nightingale, Eriksen, and Taylor (2020, 347) argue that "conceptualizations of the climate problem are embedded within the politics of whose interests are prioritized and whose knowledge are considered legitimate for addressing climate change." Digitalization means that environmental knowledge is increasingly created in "black boxes" (Bathaee 2017), relying solely on quantifiable (and thereby reductionist and selective) metrics (Kloppenburg et al. 2022, 234) that shape environmental knowledge and inform decision-making.

Digitalization changes which modes of truth production are privileged, thereby transforming how we know and how we relate to what is represented as the "environment." As boyd and Crawford (2012, 665) put it, "Big Data stakes out new terrains of objects, methods of knowing, and definitions of social life." (boyd and Crawford 2012, 665). The pursuit of environmental sustainability has gone hand in hand with a quest for more and better environmental knowledge. Digitalization responds to this call by providing environmental data that allow for improved foresight and more effective environmental management (Gabrys 2016). However, this reflexive focus on obtaining ever more environmental data tends to obscure the fact that actionable knowledge is often already at hand (Sudmanns et al. 2019, 842), whereas gathering more data could delay much-needed changes (Rehak 2024; Rehak et al. 2023, 31).

Digital technologies challenge established modes of scientific "truth" production about sustainability based on theories, hypotheses, models, and falsification. In the universe of big data, correlation is usually a sufficient indication to inform decision-making about what "works," rendering a deeper understanding of causation presumably unnecessary (boyd and Crawford 2012; Chandler 2018). Digital monitoring produces authoritative truth regimes that challenge previous environmental assessments (Gale, Ascui, and Lovell 2017). It tends to produce a kind of knowledge about nature that unduly reduces it to superficial metrics used for optimization. The imaginary of control and optimization, in turn, legitimizes the expansion of environmental monitoring tools. Digital twins, for instance, allow for future prediction, simulation, and testing of environmental interventions based on specific renderings of the environment and normative claims (Kloppenburg et al. 2022). Saltelli et al. (2024, 6) argue that digital twins "espouse a reductionist scientific logic and reinforce an economicistic vision."

Machine-learning technology provides new capacity for "environmental and predictive analysis" that alters how actors anticipate and act upon ecological problems (Kloppenburg et al. 2022, 234). The increasing deployment of algorithms – for instance in climate-adaptation planning – risk "producing hegemonising knowledge regimes" (Machen and Nost 2021). The proliferation of "environmental big data" (Gabrys 2016) offers authoritative and depoliticized knowledge claims that could displace non-quantifiable and local ways of sensing and knowing the environment (Machen and Pearce 2025, 2). While artificial intelligence (AI) applications, for example, "might shift which *kinds* of credentialed experts have a say" (Nost 2024, emphasis in original), knowledge production remains/gets concentrated in the hands of a powerful (Western and male-dominated) group of actors (Machen and Nost 2021, 4; Nost 2024; Nost and Goldstein 2022). For example, scientific evaluations of droughts in East Africa displaced traditional ways of knowing and responding to the prolonged lack of rainfall among the Masai (Nightingale, Eriksen, and Taylor 2020, 347). By excluding local knowledge, the "current techno-scientific apparatus guiding our responses to climate change is deeply disempowering for most people" (Nightingale, Eriksen, and Taylor 2020, 348).

Finally, data gaps are not accidental but mirror social marginalization in power relations. While big data sets are often associated with objectivity and being representative, they are often severely biased, contain measurement errors, and are incomplete (boyd and Crawford 2012). For example, the shortage of climate data in the Global South "is not simply the result of inadequate climatic and environmental records. Rather, it stems from colonial histories and their continuities in the current capitalist social relations that perpetuate a lack of investment in technology and infrastructure in the Global South" (Nightingale, Eriksen, and Taylor 2020, 348). Nevertheless, big data and machine learning outcomes increasingly inform decision-making by policymakers, global consultancies, philanthropies, and big tech firms in their delivery of "climate services" (Goldstein and Nost 2022, 5; Nost and Colven 2022).

New visibilities

The mobilization of digital technology and data in governing environmental sustainability transformations shapes which environmental interventions become thinkable and doable. Gathering environmental data through satellites and sensors is a prerequisite for rendering different aspects of the material world visible, intelligible, calculable, and ultimately governable (Rothe 2017). Digital technologies such as remote sensing and geographic information systems (GIS) underpin decision-making in sustainability management. By "transform[ing] *what* is made visible and *how*," digital technologies "foreground and privilege particular governance approaches and solutions" while obscuring alternatives (Kloppenburg et al. 2022, 233, emphasis in original). For example, "nature tech" is mobilized by transnational initiatives to rationalize nature-based solutions as climate-change solutions (Fransen and Bulkeley 2024). Through digital tools and altered modes of knowledge creation, biodiversity is made "commensurable, measurable, and visible and therefore governable" (Fransen and Bulkeley 2024, 88). This enables or reinforces surveillance and control practices (Fransen and Bulkeley 2024) and feeds into market-driven conservation efforts with potentially adverse effects (see Spash 2015).

Platforms and apps redirect user attention to new aspects of their environment and customize the experience based on corporate-owned big data about each customer. Thereby, they invite new modes of interacting with the environment. For example, the app Pokémon Go changed the way users navigate public space in their city (Shaw and Graham 2018), attracting them to locations marked as "arenas," where they could interact with each other in the app. Such corporate-driven visibilities often reproduce and deepen existing (spatial) inequalities. Another corporate strategy is selectively showing different representations of the city to different users, depending on their social status or other sociodemographic features (Shaw and Graham 2018). For example, users of various cultural backgrounds are guided through the same city along different routes (Shaw and Graham 2018). As Turnbull et al. (2023, 8) point out, this has material implications: "(D)igitisation produces and shapes material worlds; it does not merely represent them" (see also Gabrys 2016).

The new visibilities enabled by digital technologies are ambiguous (Machen and Pearce 2025, 4). It matters who possesses data and who can use it for which purpose. While applications developed by the company Smart Earth Technologies can render specific aspects of the environment visible, the power structures and actors behind the proliferation of these data are often hidden (Drakopulos et al. 2023). As Bakker (2022, 2024) argues, digital sensing techniques in geo- and bioacoustics could help us to "listen" to the environment and to better understand human impacts on the non-human world. However, digital acoustic monitoring is also embedded in and reinforces preexisting power structures, potentially contributing to "militarized surveillance" and capitalist accumulation (Ritts, Simlai, and Gabrys 2024, 1). Data collected about the location of endangered species for conservation purposes can equally be appropriated by poachers (Bakker 2024, 58–59). Similarly, Oliveira and Siqueira (2022) have shown how satellite data of the Brazilian Amazon were used to halt deforestation under the presidency of Luiz Inácio Lula da Silva. The same satellite data were then used to obscure the extent of deforestation under his successor, Jair Bolsonaro. In extreme cases, repressive governments could leverage digital technology such as facial recognition software and drones to identify and pursue environmental activists (Dauvergne 2021, 290–293).

Other actors, such as independent scientists, social movements, or citizen-science initiatives, can use digital tools like drones to create new visibilities that undermine official government or business accounts. Access to digital technology has become easier, empowering laypersons and civil society actors to challenge, refute, or rework official visibility and truth claims (see Zeunert and Daroy 2025). Digital tools can render unsustainable agriculture, fishing, and forestry practices visible, which has sometimes been answered by state repression. Unfortunately, many such initiatives suffer from a lack of shared data standards and quality controls.

New subjectivities and identities

Digital monitoring assigns specific roles to human and non-human actors in steering sustainability transformations. Using digital technology can help to create new subject positions and rework existing ones, thereby allocating power to some and defining it away from others. By altering modes of representation and ordering, the latest knowledge base created using digital technologies can play a role in reordering human-nature relations (e.g., Blue 2016; Luque-Ayala, Machen, and Nost 2024; Nelson, Hawkins, and Govia 2023). The knowledge produced by and through digital technologies creates new narratives of who and what is considered a (relevant) actor for sustainability transformations.

However, current power relations and knowledge regimes tend to stabilize the dominance of a specific set of actors while continuing to render marginalized groups invisible. Multinational companies such as Alphabet/Google, Microsoft, and Cisco position themselves as problem-solvers for environmental challenges (Bauriedl and Strüver 2018; Söderström, Paasche, and Klauser 2014). These corporations invest in environmental research and capacity-building, thereby (re-) shaping the knowledge base and co-designing interventions. They have also spawned and heavily influenced the "smart" city discourse (Söderström, Paasche, and Klauser 2014). Corporate-manufactured "smart" city narratives redefine the expectations for and the role of local government and individual citizens in sustainability transformations (Gabrys 2014). Citizen "participation" in the smart city is sometimes no more than an invitation to enter an online platform, act as a citizen sensor, or be tracked as a data point (Cardullo and Kitchin 2019). Local governments redefine their role as optimizers of flows in the city, for example, by installing parking-guiding systems.

Attributes of "smartness" furthermore assign actor qualities to environments like "smart" forests and oceans, engaging them as "*social-political technologies*" (Gabrys 2020, 2, emphasis in original) in combating environmental challenges. As techno-optimists argue, the living environment could "speak" to humans via digital means (Bakker 2024). This could strengthen the "rights of nature," starting with animal rights but extending to trees and other living species (Bakker 2024). While the technical means and the knowledge exist to effectively include non-humans as agents in political debates, this will, in most cases, remain a romantic idea within dominant power-knowledge regimes. Following the current trajectory, digital technology is more likely to be used "to tame species previously resistant to human domestication, deepening exploitation rather than conservation of nature" (Bakker 2022, 174).

New technologies of government

Which practices are enabled by the dominant digitalization discourses and how sustainable are they? Clearly, digitalization could offer a better information base, supporting more sustainable resource use. The availability of more fine-grained data in real time and integrated ways of processing data from diverse sources facilitates more data-driven modes of governing. The enhanced ability to generate actionable insights from data can guide operative and planning decisions (e.g., in agriculture or water management) and enable complex adaptive steering in areas such as smart energy grids or traffic control (see, e.g., Koch 2024; Rolnick, Donti, and Kaack 2023; Vinuesa et al. 2020).

However, digitalization is also used to reframe social and environmental problems as optimization tasks. This potentially reductionist understanding of digitalization for sustainability can be illustrated with applications in water management. Machine-learning methods applied to water-irrigation systems have been estimated to reduce water usage by 20 to 30% (Glória et al. 2020). At the same time, as Hartley and Kuecker (2020) argue, this approach sidelines the structural and behavioral causes behind sustainability problems. Rendering these causes visible could offer solutions on the demand side. Moreover, the water usage of the necessary machine-learning infrastructure is not considered. By promoting "reductionist notions of society and sustainability" (Bär, Ossewaarde, and van Gerven 2020), the underlying technocratic mentality undermines a more holistic and transformative approach to sustainability problems (see also Drakopulos et al. 2023 or Rehak 2024 for a more general discussion). Such narrow framings fail to ask "why society is geared toward a high-consumption, high-emissions mode of production in the first place" (Nightingale, Eriksen, and Taylor 2020, 345).

Dominant discourses at the nexus of digitalization and sustainability often enable a regime of disciplinary power and biopower. Digitalization is used to implement disciplinary regimes of surveillance, which identify at-risk groups and target biopolitical interventions on them. Some examples are adaptive planning, species tracking, conservation monitoring, and the automatic detection of anomalies and noncompliance (Bakker and Ritts 2018). Inherent to this instrumental thinking is a "powerful promise of the more perfect governance of natural entities" (Avron 2017, 363). Digital surveillance allows for remote governing, such as in wildlife-conservation management. This kind of "conservation by algorithm" contributes to a securitization of conservation, in which military logics and technology are used to fight perceived threats such as poachers (Adams 2019). At the same time, decision-making is delegated to a small number of experts who can access, understand, and act upon selected data within a digitized conservation apparatus. Emerging forms of automated governance and digital monitoring could potentially become authoritarian as they "risk… delinking humans and animals alike from deliberative, representative, or participatory forms of governance" (Ritts, Simlai, and Gabrys 2024, 2).

Moreover, at the current conjuncture, digital tools facilitate a neoliberal governing of the environment, for example, by rendering consumers in market settings responsible for sustainable outcomes (see, e.g., Steig and Oels 2025). A good example is the introduction of technologies that incentivize individuals to save energy. New legislation by the European Commission aims to bring smart meters to every household. These devices mobilize "technologies of the self" (Foucault 1988). This emergent regime of smart energy systems employs, first, mass data collection (to create norms based on averages). Second, it relies on influencing individual activities and behaviors through feedback from smart energy systems, for example, by comparing people's energy consumption to that of their neighbors. The smart meter allows energy providers and information technology (IT) companies to exercise a control function by monitoring customer behavior (Radtke 2022). However, the process of data collection is only an initial step in building a regime that controls people via "programming environments," with, for example, the help of sensor technologies (Gabrys 2014). Certainly, the mode of governance in smart cities cannot be reduced to "nudging" (Gandy and Nemorin 2019), but it is about influencing the users via structures, logics, and path dependencies that are inherent to the technologies (Wang 2017).

Alternative and more transformative visions of digital solutions for sustainability challenges exist but appear unviable within dominant governing paradigms. Digital technologies could enable mobile governance regimes and co-governance with non-human species, moving beyond territory-bound approaches. For example, "mobile marine protected areas" could adapt to species' migration patterns (Bakker 2024, 118). Some suggest that sensing non-human communication might allow non-human participation in decision-making, shifting from paradigms of "command and control" to "communicate and cooperate" (Bakker 2024, 126; Turnbull et al. 2023). However, it is important to critically evaluate whether the imposition of digital devices on non-human species genuinely constitutes cooperation and if it enables meaningful non-human participation.

To conclude, we insist that the potential of digitalization for sustainability objectives is severely limited by the power-knowledge configurations of the status quo (Nightingale, Eriksen, and Taylor 2020). Digital tools introduce rationalities of surveillance and oppression, foster optimization, and exacerbate the neoliberal status quo in sustainability management (see Schütze 2024). In the following section, we turn to the question of how different actors relate to these forms of knowing and exerting power.

Governance and actor constellations at the sustainability-digitalization nexus

Our concept of power in this section is informed by Never's (2013, 219) multi-dimensional approach to power. Never differentiates between "instrumental power" (how actors directly influence others), "structural power" (change the rules of the game), and "discursive power" (change perceptions and preferences of others). According to Giddens (1984), structure and agency are not separate entities but mutually constitutive. Actors are knowledgeable and capable of action, but existing structures shape their ability to act. While these structures – in terms of institutions, discourses, rules, resources, and so forth – shape human action, they are also reproduced and transformed by those actions. Along these lines, Avelino (2011, 69) conceptualizes power as an actor's ability "to mobilize resources to realize a certain goal." Thus, power depends not only on the availability of resources but also on an actor's ability to mobilize these resources. Moreover, the societal structures constitute the institutional arrangements in which an actor operates (Marquardt 2017). Naturally, this favors actors who are already in a position that grants them important resources to promote their views on the digitalization-sustainability nexus. Such a perspective helps problematize the role of incumbents and the structural status quo when fostering societal change.

In this section, we draw upon the sustainability governance literature to show that governing digitalization efforts toward sustainability transformations is highly contested and involves different interests leveraging their power to privilege certain forms of governance. On one hand, influential actors such as big technology companies support a techno-centric, efficiency-oriented, and depoliticized form of governance. On the other hand, various scholars and activists call for open political engagement with digitalization to achieve sustainability. To go beyond optimization and incremental solutionism, we see the need to re-politicize, democratically steer, and regulate digitalization for sustainability transformations.

Status quo bias through technical problem-solving

Digital technology, particularly to automate processes and harness data for sustainability, builds on and promotes governance forms that focus on achieving certain ends. The use of digital surveillance and control in sustainability transformations is aligned with and pushed by hegemonic interests (Nost and Colven 2022). Within the European Commission, for example, digital imaginaries such as the "twin transition" are mobilized to build a discursive link between sustainability and digital innovation (Kovacic et al. 2024). These imaginaries transform tradeoffs between sustainability and digitalization into win-win narratives, framing environmental problems as solvable technological challenges (Kovacic et al. 2024). This vision seems appealing to businesses, political representatives, and individual consumers. They can expect to lower their emissions and save resources based on improved knowledge, leading to individually optimized outcomes like lower emissions – notably without deviating too far from their existing practices. At the same time, digital innovations in the energy or water sector are said to create opportunities for value creation and employment. The underlying framing of sustainability challenges as optimization tasks leaves the structural governance conditions under which actors operate largely unchanged.

Around this issue framing, a broad discursive alliance has been forged between environmentalism, large technology companies, security firms, and others (e.g., Ritts, Simlai, and Gabrys 2024, 2). Stakeholders from the public and private sectors, academia, and civil society are uniting behind the endeavor to leverage digital technologies for sustainability outcomes. For example, the World Economic Forum (WEF) (2022) claims that digital technologies are the best way to solve sustainability problems and to achieve carbon-neutral societies as they increase the efficiency of existing technologies in sectors such as farming or energy. Various actors rally behind this approach, including development organizations like the World Bank (2024), business organizations, national environmental agencies, and non-governmental organizations (NGOs) like "Sustainability in the Digital Age" (2024) and "Digital Green" (2024). Such a wide range of different players is also assembled in the "Coalition for Digital Environmental Sustainability" (CODES) network, which is "dedicated to advancing environmental digital sustainability" (CODES 2024). In Germany, for example, the combined digital and green agenda is supported by a broad coalition of political parties, from market-liberal to environmental, like the German Liberal Party (FDP 2024) and the Green Party (Bündnis 90/Die Grünen 2022).

In its hegemonic understanding, sustainability discourse is a strong driver of digitalization, especially for fostering the integration of digital technology into people's everyday lives and societal structures. We can discern that, first, economic interests frame digitalization as a key to solving sustainability problems (Pankova et al. 2022). This goes hand in hand with creating new markets based on electronic and communication technologies, while non-digital solutions are discredited (Hall 2021; Lupton 2014; Schlumberger et al. 2024). Second, it is arguably essential for governments to simultaneously succeed in reaching sustainability goals while also expanding or supporting digital tools (Del Río Castro, González Fernández, and Uruburu Colsa 2021; Kwilinski, Lyulyov, and Pimonenko 2023; Linkov et al. 2018; Mondejar et al. 2021). Finally, the technologies themselves and their global dissemination and penetration into all aspects of life exert a gravitational pull, compelling almost all individuals to become part of this "digital movement" through a simple principle of inclusion and exclusion (e.g., widespread distribution and use of smartphones) (Etezadzadeh 2016; Mentsiev et al. 2020).

Rallying a broad discursive coalition behind the vision of digitalization as a tool for efficient resource allocation has weakened the idea of sustainability as a "resistant" momentum in the sense of a counter-narrative that emerged in the second half of the 20th century (e.g., the anti-nuclear movement, the fight of environmentalists against transnational corporations). While the "Bits and Bäume" (in English "Bits and Trees") conference series in Germany has aligned parts of the environmental movement with those campaigning for decentralized, power-aware, decolonial, free, and open-source digital environments (cf. Jankowski et al. 2023), such efforts to establish a counter-discourse remain marginalized. Today, digital sustainability often means nothing more than assimilating and aligning with the prevailing principles of the market, politics, and everyday life for most people worldwide (Ash, Kitchin, and Leszczynski 2024; Lange and Santarius 2020).

Governing transformative change through digitalization democratically

Directing digitalization toward sustainability transformations requires forms of governance that challenge vested interests, established practices, and incumbents who benefit from the status quo. Profound changes in the social and political domain need to be supported by suitable governance mechanisms and public policies that engender transformative change (Schuelke-Leech 2021) and promote alternative actors that challenge an unsustainable status quo. To realize such change, stakeholders from different policy domains and sectors must be brought together to enable coherent policy designs (Santarius, Dencik, and Diez 2023; Wurm, Wittmann, and Klenke 2023). Suitable policies involve steering resources and investment and promoting specific innovations in certain sectors. A favorable environment for the involved actors is needed, for example, by building the required skills and establishing interoperability of infrastructures (Muench et al. 2022). Thus, facilitating transformative change through digitalization requires rebuilding/unravelling structures and disempowering dominant actors.

As digital technologies span many sectors that may not normally be tightly connected, coherent policymaking is challenging. For example, digital technologies support climate monitoring, improve energy systems or logistics, enable more sustainable mobility, and foster climate-smart agriculture. Established policy actors, actor networks, and policy communities in each sector commonly operate in political subsystems that determine governance in the sector (Rhodes 2009; Weible et al. 2007). The close integration of policy networks and the vertical links across governance levels between social groups, political actors, and public-sector bodies make coordination and cooperation across these policy subsystems and domains difficult (Peters 1998, 302). Cross-sectoral governance, specifically when aiming at transformative change, will run into major obstacles due to entrenched interests and long-standing forms of cooperation. Overcoming these obstacles is a key concern in promoting sustainability transformation, and again, requires a simultaneous reform of existing governance structures and a promotion of new actors that challenge existing ways of doing things.

Democratic, participative modes of governance seem a promising way to achieve this objective. However, citizen participation in the digital age tends to amount to no more than "citizen sourcing" (Linders 2012). This usually involves a top-down approach where citizens are mobilized as a data source but are neither invited nor enabled to openly discuss alternatives to the status quo. Participation used in a top-down way is often a means of inscribing stakeholders and citizens as "responsible citizens" in hegemonic power structures. Instead of empowering these stakeholders to think for themselves, they are held responsible for a particular contribution to the public good (Oels 2019). In such a state-driven digital data mobilization for sustainability, the state – like business actors – collects data or facilitates data collection through, for example, stakeholder consultation, citizen science, or research funding (e.g., Bouzguenda, Alalouch, and Fava 2019; Cappa, Franco, and Rosso 2022; Cobo 2012). Lena Ulbricht (2020, 426) calls the state-driven data collection "demos scraping," where "scientific, political and bureaucratic elites use epistemic practices like 'big data analysis' and 'web scraping' to create representations of the citizenry and to legitimize policymaking."

The potential of participation to disrupt the status quo and to enable more radical sustainability transformations is better realized by bottom-up movements that challenge the discursive order. As Oels (2019, 150) writes: "Disruption is about forcing the powerful to renegotiate the terms of the given order by transgressing boundaries." To increase democratic legitimacy, the political process of governing digitalization for sustainability transformation should be supported and led by citizens. This would mean that citizens are not only involved as a source of input for better problem-solving. They must be empowered in such a way that they can meaningfully monitor, control, and even influence the governance of the digitalization-sustainability nexus.

New and experimental modes of governance, such as democratic innovations and emancipatory formats of citizen science, aim to empower citizens and have the potential to undermine established power constellations, rather than simply harnessing people's knowledge for predefined goals (Christine and Thinyane 2021; Ruijer et al. 2024; Sabel and Zeitlin 2012). They can help to politicize what is normally excluded from the political agenda (Marquardt et al. 2025). Such democratic innovations include formalized and often well-institutionalized participatory practices but also forms of representation that complement traditional forms of representative democracy, such as deliberative mini-publics or participatory budgeting (e.g., Capaccioli et al. 2017; Leino and Kulha 2023). Democratic innovations in sustainability governance can include aspirations for a more representative citizen voice within existing governance settings (Baber and Bartlett 2021). Yet, the democratization of digitalization also goes beyond innovations in established democratic institutions and includes more autonomous and collective citizen mobilization. In principle, these innovations "redraw the traditional division of political labor within representative systems" (Smith 2010, 3).

Citizen-driven digital data mobilization for sustainability transformations represents a bottom-up approach where citizens gain agency over political agendas. Such a bottom-up transformation through digital means can be facilitated and mediated by non-state actors such as NGOs, academics, or grassroots movements. Various forms of data are thereby used to highlight, for example, what has been neglected by the state or influential business actors, to give marginalized people a voice, or to show perspectives that are not reflected in other data sources. Digitalization thereby holds the potential to empower actors and to contribute to inclusive policymaking. It can help democratize specific fields or sectors, such as "energy democracy" (Judson, Fitch-Roy, and Soutar 2022) or "food democracy" (Bornemann and Weiland 2019), and allow for more direct democracy through digital innovations, particularly in decentralized contexts. Yet, inclusive access remains a constant challenge.

However, democratic innovations and citizen-science tools are not a neutral form of policy implementation aiming for more efficient, rational governance. Instead, they should be understood as interventions in the political landscape, engaging with competing interests, value systems, and power constellations. Some of these initiatives seek to influence climate policies, improve the sustainability of material flows, and challenge current unsustainable structures and value chains. However, the potential to democratize transformations through digitalization crucially hinges on the conditions of participation (Hamm et al. 2024). For example, Crowe Pettersson and Bassermann (2023) argue that marginalized, disadvantaged, and vulnerable groups such as some women, Indigenous people, and grassroot movements "must be at the decision-making table to decide what kind of data is needed, and to offer alternative visions for how digital technologies can be applied to the benefit of their people." Such inclusion would also encompass the possibility of refusing certain digital technologies, for instance, in cases of well-intentioned (neo)colonial developmentalism (cf. Abimbola et al. 2021, 15, 20, 22).

Nonetheless, top-down and bottom-up approaches should not be seen as incompatible opposites (Haderer 2023). There are tensions between, on one hand, potential modes of (top-down) oppression, hegemony through data selectivity and exclusion and, on the other hand, the potential for (bottom-up) participation, inclusiveness, and democratic openings (Widerberg et al. 2024). Top-down, coercive state decisions (e.g., regulating the technology sector) are also needed to enable and scale up bottom-up processes. Empowering state action can be crucial for fostering activities at the grassroots level (Bäckstrand et al. 2024). In addition, bottom-up initiatives are not automatically transformative. For example, as systematic evaluations of stakeholder participation in Local Agenda 21 processes have demonstrated, there is no automatism that stakeholder participation will tackle all three pillars of sustainable development equally (Oels 2003). Top-down state decisions may be needed to fill the gaps, for example, with respect to the environmental pillar. Relying exclusively on civil society could result in a lack of accountability of public authorities, thereby reinforcing neoliberal modes of governing (Haderer 2023). The coordination of activities at different levels from the local to the national may, in turn, be facilitated by digital tools to enable sustainability planning and governance (Koch 2024).

Thus, digitalization entails both promises and pitfalls for a democratic and people-centered approach toward sustainability, depending on how it is employed and embedded. The possibilities of harnessing digitalization, however, are also constrained by the materiality and inner logic of the technologies, an aspect to which we turn in the next section.

Technological materiality at the sustainability-digitalization nexus

This section discusses how power relations are inscribed in the physical, informational, and social materiality of digital technology and outlines the potential for a (re)politicization of technology as material objects with a social core. In this context, we understand power as the ability to shape digital systems as informational algorithmic processing infrastructures (Lanier 2014; Steinmüller et al. 1971) and as physical computation-transmission infrastructures (Brodie 2023). This ability spans from determining problem definitions, choosing certain computational means (over others) and establishing industry standards for owning and controlling concrete machinery such as data centers or sea cables. Yet, as discussed above, the actor constellation is characterized by competing interests, differing means, and social contexts, and the exercise of power is formed by preexisting digital structures and the technological materiality itself.

While the concept of technological materiality traditionally refers only to physical properties, we use the concept in a more abstract sense here to underline the digital's resource-like nature. This includes physical characteristics, informational properties and limitations, and inner and outer social dynamics. Power issues permeate the whole lifecycle of digital technology products, from cradle to grave, from inception to phase out, including the many extractive processes (physical, social) utilized. At every step of the way, design decisions are being made, starting with questions about which problem (not) to approach or how (not) to frame a task. The actual design of digital infrastructures for sustainability creates path dependencies through lock-in effects and side effects. These consequences are difficult to reverse and therefore determine which options for governing digitalization and sustainability are viable.

Physical materiality

As noted above, various stakeholders make great efforts to present digital tools as solutions for environmental sustainability. Yet, their own physical materiality and ecological footprint are often rendered invisible. Apart from lofty promises without any impact, like automated driving to reduce traffic, there are indeed already many use cases with positive results (Santarius and Wagner 2023). A few examples are circular economy optimization (Wilson, Paschen, and Pitt 2022), reduction of resource and energy consumption (Himeur et al. 2021), carbon dioxide (CO_2) emission reduction (Alli et al. 2023), smart city optimizations (Cugurullo 2020), sustainable mobility (Vermesan, John, and Pype 2021), waste separation and disposal (Wilts et al. 2021), new ways of information gathering like environmental pollution detection (Pouyanfar, Harofte, and Soltani 2022), and radically improved approaches to Earth observation (Bereta et al. 2018).

However, those digital applications come with their own resource and energy consumption (De Vries 2023), especially when we consider the necessary global infrastructures on which they depend, like data centers and internet transmissions (Marx 2024; WBGU 2019). The resource and energy impact grows even larger when we focus not only on operation but also production (e.g., destructive mining and conflict minerals) or disposal (e.g., toxic e-waste sites) of digital devices. Notably, the main ecological burden of the supply chain lies in the Global South, where extractivist practices usually follow neocolonial structures (Brodie 2023; Creutzig, Acemoglu, and Bai 2022). This remains mostly invisible to operators and users alike.

Hence, we must also problematize the need for sustainable manufacturing, operation, and disposal of digital devices, not only for sustainability-oriented applications. There are many scientific and practical approaches at hand already intended to reduce the footprint of digital tools, like green coding (Verdecchia et al. 2021), green IT (Naim 2021), green data centers (Tatchell-Evans 2017), green AI (Wu, Raghavendra, and Gupta 2022), or even systematically employing the R rule (i.e., refuse, reduce, reuse, repair, recycle). Of course, not all approaches lead to noticeable results (Nenno 2024), and reliable end-to-end analyses are difficult to conduct (Strubell, Ganesh, and McCallum 2020; van Wynsberghe 2021). The current overall energy consumption of digital infrastructures is estimated to be around 4.5% of global energy use and rising increasingly fast (Lange, Pohl, and Santarius 2020). Emission levels are comparable to the present global civilian air traffic. Interestingly, the operation of IT systems and their associated data transfer are becoming ever more energy efficient; however, demand is rising even faster, and therefore the overall energy consumption is also projected to continue to expand (Fouquet and Hippe 2022).

Nonetheless, the claim persists that digital tools and services will help to dematerialize the rest of the economy. According to this narrative, resource-intensive brick-and-mortar shops could, for example, become slick online services, with additional savings achieved in mobility, construction, and other realms (Accenture Strategy 2015). However, this digitalization promise of decoupling growth from resource use does not seem to materialize (WBGU 2019). Rather, many studies show how strong digital rebound effects in different sectors lead to ever-increasing absolute resource and energy use (Bergman and Foxon 2023; Freitag et al. 2021; Lange, Pohl, and Santarius 2020). Ultimately, energy and resource consumption of the whole IT ecosystem is not merely a technical issue, but a complex societal one (Bergman and Foxon 2025; Kunkel and Tyfield 2021). Instead of buying into hegemonic narratives, individual use cases of digital products should be subject to public scrutiny: Is the duration of use relevant, for example, short or long-term? Are the purposes themselves sustainability-supporting or preventing, for example, smart parking for cars or smart biking infrastructure? Do proposed sustainability solutions rely on unsustainable means, such as energy-intensive proof-of-work blockchain technology? And on a more fundamental level, does a given problem actually need a digital solution? These and other questions can help to repoliticize the often-hidden physical materiality of digital applications.

Informational materiality

Looking into the more technically informed literature, we find that "the digital" is not a monolithic entity with homogenous properties. It is also not a universal tool applicable to every use case (Coy et al. 1992; Floyd et al. 1992; Lessig 1999). Instead, the digital should not just be described as a complex toolbox but rather as a material like cement, where access and shape are formed by power relations and the societal context in which it is embedded.

While the informational materiality of digital technology implies some general properties and characteristics, the digital has no concrete form or purpose by itself. Tangible artifacts must be shaped out of it. While the basic building blocks like algorithms, systems architectures, and ways of software engineering shape digitalization's informational materiality (e.g., Cormen, Leiserson, and Rivest 2022; Russell and Norvig 2022; Tanenbaum 2008), concrete properties and characteristics arise from many choices during design and operation. Systems can be data-intensive or not, highly personalized or anonymous, highly centralized or largely decentralized, even anarchistic (Klischewski 1996). System creators and operators shape the systems according to their requirements. Explicating those requirements is a central aspect of systems engineering (Floyd et al.

1992). While the actors are also embedded in diverse power structures, managerial decisions simultaneously shape digital technologies and their applications.

Acknowledging that informational materiality is subject to deliberate choices provides leverage points to a truly transformative use of digital tools. Fundamental questions should be subject to public debates to (re-)politicize informational materiality: How should the digital artifact (not) relate to other artifacts? Proprietary and closed digital artifacts cannot be collectively organized, shared, or interoperated; but they can be when using free and open-source software (FOSS) combined with open standards. What should (not) be quantified, datafied, and automated? Democratic negotiation cannot be automated, but electricity-grid balancing can be to a certain extent. In principle, climate and weather data can be entirely captured, but the quality of human connections or happiness can only be assembled in a very limited way. How should we organize the specific digital materiality? The digital can either scale to centralize power or scale to decentralize power. How should social data be collected and used? It can be deployed to do individual profiling and tracking or to aggregate data for public use and collective decision-making.

Social materiality

Digital artifacts have a cultural and social history. They are the product of individual and collective decisions, practices, and structural factors (Brodie 2023; Floyd 1999). As an example, IT itself has its origins in the military sector. The United States invested heavily during the Cold War to decrease the size of a computer, from filling a whole room to fitting into a missile. Without these political decisions and military investments, mobile devices would probably not have their current form (Weizenbaum 1976). Similarly, the modern-day underwater internet sea cables still largely go along the old colonial telegraph network paths (Müller 2016; Thorat 2019), illustrating a long and deep tie between technology development and political realities.

Furthermore, current socioeconomic conditions, laws, economic incentives, actors' interests, and power structures continue to shape digitalization. This leads to global monopolies and a concentration of power previously unseen in other sectors (e.g., Torrent-Sellens et al. 2022). Big tech players such as Alphabet/Google or Microsoft have huge budgets for global lobbying. This influence allows them to dominate and shape administration, business, education, and military affairs, as well as the prison system (Kwet 2019). This domination reveals the close interdependence of technology design with existing power constellations. Simultaneously, digital artifacts have social effects, which influence the digital artifacts again. Therefore, it is impossible to meaningfully imagine digital artifacts independent from their social context (Weizenbaum 1976). Hence, outside purely technical discourses, the term technical system always means socio-technical system (Ropohl 1999).

The social materiality is further shaped by the social dynamic "inside" the digital artifacts. The type of inner governance of a project fundamentally shapes the IT systems being created and the uses for which they are suitable. Is the operational/business model designed for the long term? Is there equity among stakeholders? What kind of modeling and data gathering is intended? What environmental and social requirements are considered key? Does it follow FOSS practices or rather the proprietary paradigm? Do environmental sustainability issues matter in the sense of whether the artifact is designed to last, is it modular, or not? Is participatory design a goal? Software and systems engineering, for example, is usually a collaborative effort in which the involved actors' approaches, values, and visions must be coordinated. The governance of these issues can vastly differ from one undertaking to the next. Some projects have strict hierarchies – Microsoft's Windows or Apple's iOS – and some even have a "benevolent dictator for life" (e.g., the Linux kernel). Others have a steering council model like the Python project (after Guido van Rossum stepped down). Still others follow complex committee-driven democratic models, as is the case for the Debian project. There are even instances of dedicated "user councils" that create quasi-democratic and proto-representative channels between "inside" and "outside" (e.g., the Ubuntu project; see Cánovas Izquierdo and Cabot 2023; Guagnin 2020).

However, the full complexity of the environmental impact and the informational and social materialities (Brodie 2023) are usually hidden from the users. This invisibility points to an inherent design conflict in IT infrastructure or the "transparency paradox" (Hempel 2017). Reducing or hiding the complexity of complex tasks by, for example, automation, is a central reason and necessary condition for using IT infrastructures in the first place (Chazette and Schneider 2020; Star 1999). At the same time, the cultivation of invisibility to hide decisions, agendas, and impacts is a common approach to staying in power for powerful actors in many realms (Hempel 2017).

The social embeddedness and materiality determine the overall direction of a digital artifact. When introducing digital technology for sustainability objectives, the implicit and explicit problem and solution definitions are highly political. To (re-)politicize the digitalization-sustainability nexus from the perspective of social materiality, we must collectively engage with questions such as: What kind of inner governance is deemed appropriate (e.g., dictatorial or democratic)? What business or operational model is intended (e.g., growth and profit or digital sufficiency)? What kind of innovation is being pursued (e.g., techno-solutionist or holistic socio-technical)? What type of user engagement is desired (e.g., short-term affective or conscious cognitive)? What kind of user involvement is aimed at (e.g., passive service access or active co-creation)? What type of social ideals are supported (e.g., libertarian free market or sustainably coordinated digital planning)? How are risks (re)distributed through applications (e.g., individualized climate insurance or collective climate safety)? All those questions highlight how the digitalization-sustainability nexus is shaped, especially by dominant power relations. And those questions also point toward possible answers regarding how this nexus can be reshaped toward sustainability.

Toward sustainable socio-technical information systems

As shown, digital technology and digital infrastructures have their own environmental, informational, and social materiality. They reflect and perpetuate societal conditions and power structures, unless deliberately shaped otherwise. The deep embeddedness of unsustainable practices impedes conceptualizing and implementing meaningful digital sustainability transformations. The capacity of hyperscale data centers is expected to triple within the next three years, with energy, water, and other resource use rising in tandem (Langley 2023; Marx 2024; O'Brien and Fingerhut 2023). If this development, for example, by companies like Alphabet/Google and others, is economically viable, digitalization can in principle never be sustainable, regardless of specific current actors.

The economic framework conditions allow, and even encourage, the current resource and data-hungry AI hype (Marx 2024; Rehak 2024; Rehak et al. 2023) that is furthering the ongoing destructive effects. However, the societal embeddedness of digitalization also points to its non-deterministic character: Like society itself, its parts can be (re-)politicized and therefore altered. This requires reconsidering many underlying assumptions of current digital developments to address and then resist anti-sustainability-oriented hegemonic power and influential techno-solutionist narratives (Schütze 2024). To reach globally just and democratic net-zero societies with decarbonized circular economies and strong biodiversity protection, the currently overall aimless digitalization must be conceptualized and shaped into a strategic digitalization in line with the sustainability goals (e.g., Bärnthaler 2024; Santarius, Dencik, and Diez 2023).

On the level of digital materiality, we identify two leverage points for such a strategic digitalization. First, digital artifacts like social media, online shopping, and video-streaming platforms are mostly discussed in their current form as provided by profit-driven corporations. Given the informational materiality characteristics discussed above, these and many other artifacts could be designed and implemented in completely different and sustainable ways beyond commercial monopolistic aspirations and negative network effects (Doctorow 2023). This distinction between social function and concrete digital implementation also opens the imaginative space for alternative digitalizations. It could directly inform responsible innovation and investment (Mazzucato 2015) and therefore be a crucial lever to reshape digitalization toward sustainability. We must closely connect those insights with ideas of digital sufficiency (Santarius, Dencik, and Diez 2023), public digital services, global free and open standards/software for evading lock-in effects and allowing long-term repairability (Bonvoisin 2016), and related governance questions. For a sustainability-oriented strategic digitalization, promising paradigms like low-tech, solar punk (Reina-Rozo 2021), needs-based Doughnut Economy (Raworth 2012), digital degrowth (Kwet 2024), or convivial technology (Vetter 2018) might need to replace the currently employed unsustainable scalability, generalizability, AI-first, and efficiency paradigms. However, implementing the new paradigms is a profound task for societies. It involves commitment from policymakers to businesses, from scientists to practitioners, from civil society to art and culture. Addressing these questions also requires open forms of governance, such as democratic innovations as outlined above.

A second leverage point for strategic digitalization that aims at sustainable materiality combines environmental and social sustainability. Societies in a digital constellation (Berg, et al. 2020) also organize an information ecosystem comprising communicative, cultural, political, or economic aspects mediated through and taking place within digital artifacts. Hence, those artifacts are digital tools for acting on the physical world and for extending it. Sustainability-related practices like digital co-production, commoning, free software, and open standards (Bollier and Helfrich 2012; Ostrom 1990) have substantial positive effects on environmental sustainability but also contribute to social sustainability (Jankowski et al. 2023). (Re)organizing software, hardware, and knowledge practices around participation and collective stewardship helps technical maintenance and repair become visible (Hempel 2017) and valued as the digital care work they are (Jarke and Büchner 2024; Zakharova and Jarke 2024). Building on such practices leads to digital sufficiency and resilient social structures (Jankowski et al. 2023).

Although many small and medium-sized projects already practice these activities, it will require broader societal engagement to overcome the societal framework conditions that still favor commercial expropriation and profit-driven digital unsustainability (Doctorow 2023). Only by resisting and changing the power structures of the status quo can the "glass ceiling of transformation" (Hausknost 2020) finally be overcome.

Concluding discussion: (re-)politicizing the digital in sustainability transformations

Digitalization is neither a silver bullet to solve sustainability issues nor, in principle, a barrier. Instead, its emancipatory and democratic potential depends on the feasibility of (re)politicizing sustainability issues and the sociopolitical foundations they rest upon. As we have outlined above, digitalization can endanger or enhance sustainability transformations. It becomes a threat when knowledge, discourses, governance, and technological materialities are depoliticized and detached from their sociopolitical environments, norms and values, knowledge infrastructures, and power dynamics. At the same time, digital tools can empower marginalized voices and perspectives in sustainability debates.

Figure 2 shows the dominant power constellations in knowledge, governance, and technological materiality at the sustainability-digitalization nexus. We briefly summarize these arguments from the preceding sections in the following discussion before concluding with limitations and avenues for future research.

First, we have illustrated how the modes of knowing the environment and rendering it governable are being reworked through digital tools and discourses surrounding digitalization and sustainability. Dominant discourses deepen managerial techno-fixes in the name of sustainability while reinforcing unsustainable ways of living and governing. Digitalized (real-time) data has enabled efficiency gains in some sectors. However, the increasing proliferation of environmental and behavioral data legitimizes new forms of governance that mostly reinforce well-known rationalities of biopolitical surveillance, neoliberal responsibilization of consumers, and technocratic solutionism. Ultimately, digital data often helps promote the modern state's simplified and often authoritarian, top-down models to organize society (Scott 1998).

Second, we have shown how a wide array of actors, including private corporations, public administrations, and international organizations, rally behind reductionist and depoliticized discourses and

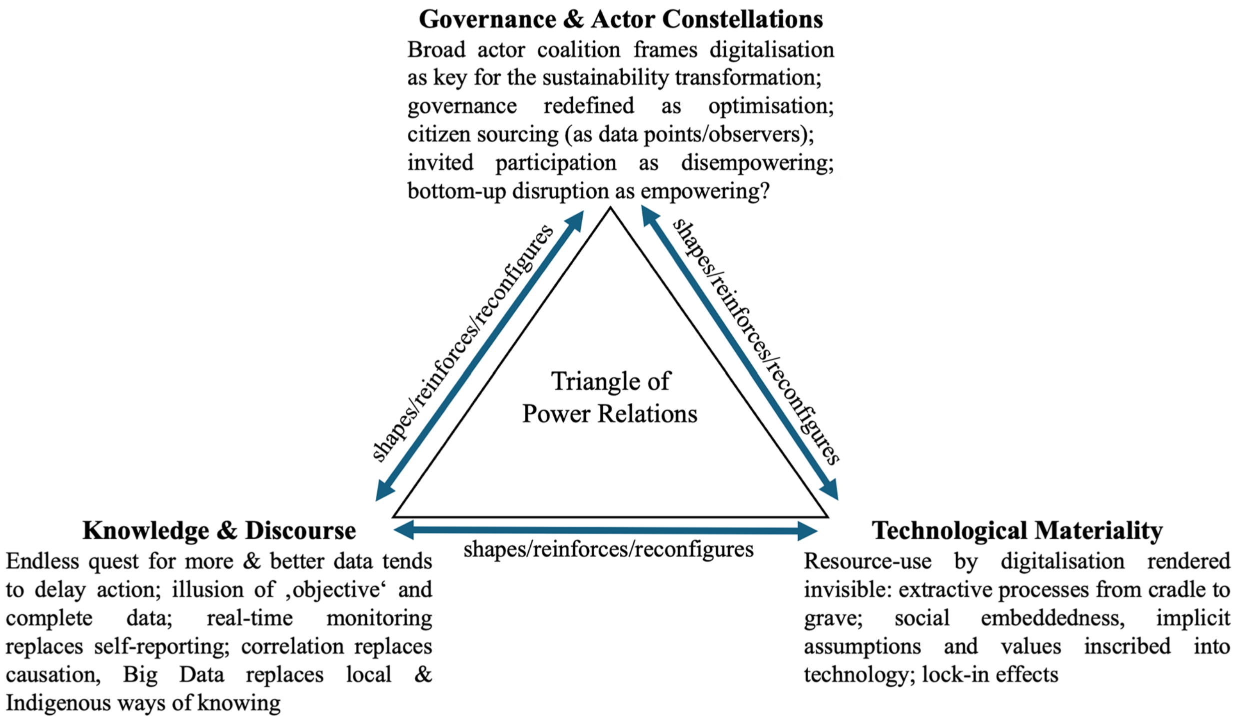

Figure 2. Identified power constellations at the sustainability-digitalization nexus.

practices of optimization through digitalization while marginalizing debate about the structural drivers of unsustainability. Digitalization raises expectations that civic and democratic participation could be strengthened, but these have not yet materialized. Instead, citizens are often mobilized as a data source in a top-down manner, unable to demand alternatives to the current social, political, and economic order. Such alternatives include redistributive measures toward environmental justice, institutionalized citizen participation in policymaking, and critique of the growth-oriented development model. If digital tools are employed to constrain debates about such alternatives, this can – and in the worst case will – result in incapacitation rather than empowerment.

Finally, we have demonstrated that the potential of digital technology for sustainability transformations is also inherently shaped by the materiality of digital technology. Implicit assumptions, values, cultural embeddedness, political and economic interests, and conditions of production and use remain hidden when only treated as "mere technology." The path dependencies and lock-in effects of technological development are naturalized, thereby concealing inherent power relations and remaining degrees of freedom. To unlock the digital potential for sustainability transformations, societies need to acknowledge the complexity of modern socio-technical systems with their inherent conflicts and contestation and govern them in a more open, participatory, and reflexive way. Rather than relying on top-down, technocratic solutions driven by big data, we should recognize that digitalization creates new risks and uncertainties that demand participatory governance rather than centralized control (Beck, Giddens, and Lash 1994). In short, the digital materiality must also be (re)politicized.

Digitalization is currently unfolding in primarily market-driven ways (Schütze 2024), heavily relying on outright extractivist and neocolonial practices (Kwet 2019). As digital technology largely reflects societal circumstances, it should be no surprise that digitalization currently reproduces inequitable (O'Neil 2016), unfair (Dressel and Farid 2018), racist (Noble 2018), classist (Eubanks 2019), sexist (Criado Perez 2020), unsustainable (Creutzig, Acemoglu, and Bai 2022), and primarily tech-centered and profit-driven (Morozov 2013) conditions. So far, sustainability-oriented digital practices that provide transparency, co-creation, and participation in design have little or even negative economic relevance. As long as the majority of sustainability costs can be externalized (e.g., neocolonial sourcing of materials, low wages in production, emissions in operation, toxic waste in disposal), digitalization is likely to be a "fire accelerator of the climate catastrophe" (WBGU 2019, 4) with detrimental effects on other sustainability challenges.

The potential of digital technologies to tackle environmental sustainability crises could be unlocked by opening the current depoliticized configuration to societal deliberation and renegotiation. These deliberative processes should not be limited to choosing the best digital technologies but should consider their societal implications and repercussions. Digitalization cannot spare us from political conflicts and deliberative processes about which sustainability futures we as societies collectively envision. Instead of buying into overoptimistic narratives, we suggest centering fundamental questions such as: Which problem are we trying to solve with digital technology? Whose interests are served? Who benefits and who loses from digitalization? And which power relations are challenged or reinforced by digital innovations? Proponents of digitalization for real sustainability transformations need to question presumably "objective" and "neutral" data sets, exposing their inherent biases, data errors, and gaps and making transparent the values and norms that inform data collection and usage. They also need to expose and subject to public scrutiny implicit assumptions like growth-orientation and coloniality. Alternative forms of citizen empowerment and new principles, such as data sufficiency, are needed for a transformative governance approach. In the realm of design and infrastructure, efforts are needed to make visible the physical, informational, and social materiality of technology. Initiatives like the low-tech movement could offer alternative narratives for understanding and using digital tools for sustainability transformations (Tanguy, Carrière, and Laforest 2023).

Table 1 summarizes the ways in which the mainstream notion of the sustainability-digitalization nexus is largely depoliticized. The second column outlines the potential levers for a (re-)politicization of sustainability knowledge and discourses, governance and actors, and the technological materiality of digitalization.

While this article provides a theoretical reflection and critique of the sustainability-digitalization nexus, it is important to acknowledge its limitations. First, the analysis is illustrative rather than empirically grounded. Second, while we highlight the role of power relations and economic interests in driving digitalization, we do not adopt a historical materialist perspective to systematically examine and trace the roots of these dynamics. Consequently, the article offers limited discussion of how the deployment of digitalization for sustainability is constrained by an accumulation regime oriented toward growth and

Table 1. De- and re-politicization of the sustainability-digitalization nexus.

	Modes of depoliticization	Potentials for (re-)politicization
Knowledge and discourse	Real-time monitoring, striving for N = all, producing quantified digitalized representations of nature; drawing insights from correlation and probability/machine learning, marginalizing local/Indigenous knowledge.	Expose inherent biases, data errors, and gaps in data sets; expose implicit assumptions and values in knowledge production (e.g., coloniality, growth-orientation); create (a plurality of) (digital and non-digital) counter-narratives and discursive contestations; include Indigenous and local knowledge; use theory to develop causal and constitutive models.
Governance and actor constellations	Data-driven forms of steering reduce governance to technocratic optimization; citizens' role is reduced to data points/sources; evidence-based policymaking is represented as presumably neutral and apolitical.	Uncover power dynamics and vested interests; phase out unsustainable modes of production and consumption and the structures that privilege them (e.g., subsidies); use digital tools where needed (e.g., decentralized grid management); redistribute between winners and losers of sustainability transformations; use digital tools to challenge governmental claims (e.g., citizen science); embrace democratic innovations and make sure they are linked to democratic decision-making structures (e.g., citizens' assemblies).
Technological materiality	Profit-driven data extractivism in private ownership; monopoly ownership structure; technical determinism, overstating path dependence, hiding the materiality of digital technologies, and naturalizing inherent design decisions.	Make the resource flows and work that sustain digital infrastructures visible and governable; make choices in design and operation visible and governable (e.g., FOSS, interoperability of platforms, digital sufficiency); develop visions of alternative materiality (e.g., low-tech movement).

sustained by supporting regulations and actor constellations (Bärnthaler 2024). Finally, alternatives to the dominant digitalization-sustainability narrative, as articulated by local movements and prefigurative practices, are crucial for challenging the status quo. While these remain underexplored here, they warrant further investigation in future research.

Future research should build on earlier critiques of techno-optimism in sustainability research (e.g., Alexander and Rutherford 2019). Critical data studies offer a good starting point to do so (e.g., de Albuquerque et al. 2021). More specifically, researchers could ask, for example: Who drives discourses that promote digitalization as a solution to the sustainability crisis? Who benefits and loses most from the introduction of new tools and rationalities? Thus, more research is needed to overcome a "politically toothless and historically shallow non-neutrality approach" (Almazán and Prádanos 2024, 8) for the sustainability-digitalization nexus. Another avenue for critical interdisciplinary research concerns the potential of digitalization in the field of democratic innovations and the potential to "regain control" (Stucke 2022) over data and the way we use it. How is digitalization integrated into regimes of environmental management, many of which have proven to rely on unjust and ineffective governing techniques? On the level of design and infrastructure, how can harmful materialities be exposed and what is needed to disrupt the unsustainable status quo? Can these materialities be made visible without relying on other digital tools and approaches that worsen digital technology's ecological/human footprint and reinforce hegemonic modes of knowing? Future research should build on emerging work that problematizes the "technocracy-democracy dilemma" due to the rise of AI in times of climate change (Coeckelbergh and Sætra 2023).

Digitalization does not offer a shortcut to social change. We need to move from incremental digital fixes to comprehensive sustainability transformations. This will require a fundamental change in the social, economic, and political order away from growth orientation, extractivism, and neocolonialism and toward a system where digitalization serves the sustainability goals of the people. Broad participation and social movements are needed to challenge vested interests that sustain the unsustainable status quo. Only then can digital tools play a positive role in sustainability transformations.

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