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Editorial
Across the Layers of Planetary Matter, Data Infrastructures, and Knowledge Production

Stefan Laser
Ruhr University Bochum, stefan.laser@rub.de

Leman Çelik
Ruhr University Bochum

Estrid Sørensen
Ruhr University Bochum

The task at hand: Thinking across the layers

Knowledge has weight. It accumulates in infrastructures, flows through cables, and settles in data centres that consume land, water, minerals, and energy on a planetary scale. Yet this weight is rarely felt in the everyday practices through which knowledge is produced, circulated, contested, and consumed. In 2009, a news report generated attention by making a comparison: the amount of energy spent making two Google searches roughly equals that of boiling water for a cup of tea. That comparison has since been updated for the age of generative AI, with the claim that a large language model (LLM) query uses around five times more energy than a Google search. This statistic is situated within broader concerns about the rapidly increasing energy demands of AI infrastructures (e.g. Zewe, 2025). One may add that the energy consumed by material infrastructure mobilized for a single exchange with an LLM now comfortably exceeds what it takes to walk to a library, pull a book from the shelf, and read it by the window. Such comparisons have done something important: they have made visible a connection between knowing, data infrastructures, and the planetary relations involved that usually remain hidden. The comparisons thus help to link debates about the climate effects of data infrastructures and debates about the knowledge produced through these infrastructures; debates that generally unfold separately, as if they had nothing to do with each other. But the comparisons have also done something misleading: by framing the problem as a matter of individual choice and digital consumption, they place the burden on users. They deflect attention from the broader hinterland of actors, practices, alliances, and power regimes that sustain data infrastructures (Pasek, 2023; Vaughan et al., 2023). What gets lost is everything between the layers of end-user knowledge, data infrastructures, and planetary matter. This special issue offers empirical studies of the interrelations between knowledge, planetary matter, and data infrastructures alongside conceptual discussions of how to think across these layers.

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Science and Technology Studies (STS) as a field finds itself at a juncture, which is the point of departure for this special issue. On the one hand, there is a rich body of work documenting the very material consequences of ostensibly immaterial digital practices and infrastructures: the CO_2 emissions of cloud computing; the territorial footprints of server farms; the 'slow violence' of electronic waste; the unequal representation of knowledge about the social and environmental harm of extractive practice; the material assemblages that make up software and hardware, and so on (Gabrys, 2011; Hu, 2015; Velkova & Plantin, 2023; Edwards et al., 2025). On the other hand, the conceptual vocabulary at hand to connect data infrastructures and planetary matter with knowledge practices remains underdeveloped. While STS scholarship offers an advanced vocabulary for conceptualising sociomaterial knowledge (e.g. Edwards, 2013), it is less practised at also articulating the role of planetary matter in this heterogeneous relationship. The challenge to do so is epistemic as much as it is political: how we think the link between knowledge, planetary matter, and data infrastructures shapes what kinds of questions are asked; what practices, worldings (Tsing, 2010), and interventions appear possible, and for whom.

Several strands of work are inspirational for the task at hand. Critical data centre studies identified planetary concerns as a pivotal aspect of the field. Famously, Cubitt et al. (2011) asked whether cloud computing has a silver lining. A rich body of literature relates data centres to the extended planetary relations in which these data infrastructures are entangled, often related to energy and minerals. Issues of water (Hogan, 2015; Maguire & Winthereik, 2021), air (Vonderau, 2019; Au, 2024), heat (Velkova, 2016, 2021), territory (Parker, 2019; Munn, 2021), extractivism, displacement of Indigenous people, and colonialism (Burrell, 2020; Lehuedé, 2022; Velkova & Plantin, 2023), as well as energy (Carruth, 2014; Bresnihan & Brodie, 2023, 2025; Pasek et al., 2023; Lopez & Diguet, 2025), and particularly how digital infrastructures are run on fossil fuels (Cubitt et al., 2011; Ensmenger, 2018; Hogan, 2018; Brevini, 2020; Brodie, 2020; Atkins et al., 2021; Crawford, 2021; Dourish, 2022; Lally et al., 2022; Monserrate, 2022) have been the focus of attention in the literature on the relation between data infrastructure and environmental issues (Edwards et al., 2025). Infrastructure studies and scholarship of political ecology have shown how fibre optic cables, base stations, data centres, and internet exchange points are territorial actors with geopolitical weight (Blum, 2013; Starosielski, 2015; Pickren, 2018), as are e-waste materials (e.g. Gabrys, 2011; Lepawsky, 2018; Laser, 2020). Time and again these studies show how data infrastructures are extended and almost invisibly woven into the fabric of the planet.

Despite the plethora of studies thus thinking across the layers of planetary matter and data infrastructures by attending to the interrelationship between digital infrastructures and planetary conditions, fewer studies think across one more layer: knowledge production. Among those who do so is Rella (2023), who suggests a material epistemology and notes that it is not enough to ground digitality by stressing that digital infrastructure has, as it were, a heavy material backdrop. Instead, hardware itself has to be understood as a knowledge machine. Crawford and Joler (2018) discuss the chain of extractions and exploitations that underpin a single AI system, likewise showing how the quantification of nature is constitutive of contemporary knowledge production (see also Crawford, 2021). From a neo-Marxist perspective, Pasquinelli (2017) situates planetary extraction within a specific order of intellectual labour in capitalist societies, a line of argument that connects with broader debates about the political economy of data (cf. Hecht, 2023; Papadopoulos et al., 2023). In a similar vein, Bresnihan and Brodie (2025: 143) stress that knowledge regimes (for instance, of climate mitigation) rest on the shoulders, and bogs, of monopoly tech companies that have planted data centres on troubled (in their case, Irish) land. Taken together, these contributions make a compelling case that knowledge practices and planetary matter are deeply intertwined; mediated, in each instance, by data infrastructures. As STS scholars, we are committed to analytical frameworks beyond totalising gestures. What STS methodologies can offer to conceptualising and to studying the intersections of planetary matter, data infrastructures and knowledge is to trace entanglements without

resolving them prematurely; and to attend to the empirical particularity of how these relations in practice are made and remade in many different ways.

The motivation behind this special issue is that new methodologies and particularly new thinking and concepts are necessary to closely relate the socio-material to the epistemic-planetary; to think across the layers of planetary matter, data infrastructures, and knowledge production. The contributions take up these challenges and investigate the relationship between knowledge practices, data infrastructures, and planetary matter, by testing different concepts and methods adequate to the complexity of what is at stake, and by providing empirical insights.

Planetary matter

In the title of the workshop, which gave birth to the idea of this special issue (see below), we used the notion of 'planetary resources.' Since the notion of resources draws intellectual attention towards what is turned into goods and assets (industrial, often capitalist ones), we soon replaced the term with 'planetary matter.' 'Matter' hints at the two ways in which the notion of issue (and controversy) has been discussed in STS (Latour, 2004; Marres, 2007; Venturini, 2010; Venturini & Munk, 2022): by attending to the materiality of relations and by highlighting matters that are of concern. In contrast to controversies, planetary matter cannot be resolved, only engaged with and transformed. Planetary matter is not an external, inert entity out there, as 'resources' are often framed. Spivak (1999) introduced planetarity as a critical counterpart to globalisation, a non-totalising concept that acknowledges rupture as well as alterity (Elias & Moraru, 2015). The complexity of planetary relations reveals that planetary matter is not (only) an object of analysis, but an intellectual orientation. It keeps in view the weight of what is at stake and the irreducible openness of how the stakes might be encountered.

Although we (not least in our contribution to this issue) are keenly interested in the analytical orientation offered by the notion of planetary matter, the term also refers to empirical phenomena. While knowledge and data infrastructures are established terms in STS, and we know what empirical phenomena to imagine and which discourses to relate to when using these terms, 'planetary matter' is empirically vague, and deliberately so. With the notion of planetary matter, we offer a term to think about entanglements that STS tends to underappreciate, and which are still easier to ignore than to include. The term is an invitation to inquire into complex and contested planetary phenomena that matter for knowledge and data infrastructures, particularly those which are currently in a state of changing dynamics due to the Anthropocene. It is both an epistemic and empirical challenge to account for planetary matter in STS thinking and research. We propose the term 'planetary matter' as a question that searches for answers, and for conceptual, ontological, and empirical clarification.

The five articles included address the question of the intertwinements of the layers of knowledge, data infrastructures, and planetary matter in different ways. Planetary matter is not a key term in any of the articles, whereas they all use the terms knowledge and data – or digital – infrastructures. In this introduction, we will present the articles by reading them from the perspective of planetary matter, asking what they identify as planetary matter and how they contribute with conceptual approaches and empirical insights to thinking across the layers of knowledge production, data infrastructures, and planetary matter.

The articles of the special issue

The journey towards this special issue started with an online workshop series titled *Across the Layers: Scientific Knowledge Production, Planetary Resources, and Data Centres*[1], a setup shaped by the repercussions of the COVID-19 pandemic. The main title 'Across the Layers' draws on an established mode of thinking in informatics dividing both software and hardware operations into distinct layers, each responsible for a certain function. Attending to the astronomical body called Earth, geologists too attend to layers. They acknowledge and examine the formation and ongoing transformation of layers of rock – or 'strata': a term and mode of thinking also known from Deleuze and Guattari (1987). Modern science

and modern culture are founded on the ability to isolate research objects (Stengers, 2018) – e.g. into layers – from their entanglements with planetary phenomena of other scientific domains. This isolation also enables interventions that are extractivist and lack response-ability (Haraway, 2016) to such entanglements, and it fosters an inability to think across layers. We propose the heuristic of layers to acknowledge the performativity of categories and their architecture, yet also to cut across levels of abstraction as well as of materiality.

Based on the fruitful exchanges and the overwhelming resonance of the online workshop series we later reunited for a writing workshop, which started the journey towards this issue. During the workshop, our university's cloud system was shut down due to an excavator doing maintenance work and cutting a cable somewhere between our edge infrastructure and the data centre hosting our virtual material (Abels et al., 2024). This event of the breakdown is in itself rather unremarkable: transport infrastructures were under maintenance, and the people operating excavators accidentally cut a cable, simply doing their jobs, apparently unaware of how close transport infrastructures on the surface are to data infrastructures below. What the incident makes difficult to ignore is how the actual earth being dug kilometres away can disrupt the fragile architectures on which knowledge practices depend (cf. Rubio et al., 2025), sending emergency crews scrambling to restore a connection whose existence we had not considered problematic before assembling for our discussion. It made for a good opening of the workshop, giving participants a very lively experience across the layers of planetary matter, knowledge production, and data infrastructures.

The first of the five articles is written by the issue's editors. The ambition of this conceptual piece is to re-think knowledge as not merely dependent on planetary resources, but as itself being planetary. This is motivated by concerns over science's lack of engagement with how its very process of production is involved in shaping the planet. The German National Academy of Sciences Leopoldina recently invented the term 'science accessorial' to downgrade attention to, amongst others, the environmental impact of scientific knowledge production to mere decoration. It thus excluded such concerns from what is to be considered real science (Krieg et al., 2025). STS has intervened crucially to the understanding of scientific knowledge by emphasising its social and technical ontology. Sørensen et al. take a further step in this issue and argue for an understanding of knowledge as also planetary. The planet is not accessorial; it is inherent to scientific knowledge. The authors question how to think of scientific knowledge as planetary, and they identify data infrastructures as a key mediator between scientific practices and planetary matter. At the heart of this is the goal of developing a sensitivity to researching knowledge as extended relations that traverse diverse heterogeneous domains and boundaries while remaining connected within one shared world. The article combines literature on sociotechnical knowledge production with decolonial, feminist, and other critical and creative works on planetarity to develop the planetary studies of scientific knowledge. This implies a thinking that moves from a flat ontology to envisioning a spheric ontology of scientific knowledge as extended heterogeneous and transforming relations that cut across its own practices, digital infrastructure, and planetary matter. The article contributes an understanding of planetary matter that refuses to treat it as accessory, resource, or backdrop for scientific knowledge. Rather, the article points to the extended consequences of conceptualising scientific knowledge as not only social and technical, but also planetary.

Tremčinský's contribution on energy, information, and batteries allows for a different thinking across layers of planetary matter, digital infrastructures, and knowledge production. The author emphasises that in capitalist markets, energy cannot exist without specific information techniques that turn its flows into abstract stocks, which make energy marketable. He calls these stocks 'batteries' and emphasises their informational character. In his analysis, what we call planetary matter is rather planetary flows, i.e., energy flows, whose fluid (or drifting) character makes them incompatible with the capitalist economy (cf. Battistoni, 2025). Tremčinský points to information and specific knowledge practices as layers (in our vocabulary) added to planetary flows, which organise them into different modali-

ties (account, waste and stock) of virtual, Bitcoin and grid-scale batteries, i.e., into legible and marketable forms. The paper thinks carefully through materialities – the distinct physical properties of intermittent renewable sources, the entropic loss in Bitcoin mining, the electrochemical behaviour of lithium-ion cells – and their entanglement with knowledge practices of valorisation, accounting, and evaluation. The analysis displays the productivity of thinking across the layers of knowledge and planetary matter – as flows – to understand how their entanglements create particular kinds of socio-economic forms, in this case capitalist market goods. With reference to Clark and Szerszynski's (2021) seminal work on planetary social thought, Tremčinský concludes by pointing to the term 'drift economy' to identify entry points to organise the layers of knowledge and planetary matter otherwise.

Maguire's article introduces us to a group of scientists and speculative designers who work collaboratively to develop biotechnologies for using the DNA of living plants as data storage. They thereby reconfigure what Maguire calls the planetary-digital-knowledge nexus, i.e., the co-constitution of planetary conditions, digital infrastructures, and knowledge production, in which these are recursively entangled through overlapping relations, interdependencies, and complicities. The scientists' and designers' ambition resonates with the aim shared by this special issue of reducing planetary harm of knowledge production and its use of digital infrastructures. The scientists in Maguire's case explain that in the process of storing data in the DNA of living plants, carbon is bound rather than emitted. However, Maguire points to how this highly innovative project is folded into standard technoscientific practices that make potential harm absent – e.g. harm to the plants and their habitat. The author thus emphasises the need to consider carefully the configuration of what he calls the planetary-digital-knowledge nexus of innovative biotechnologies to avoid extractivist logics emerging even through the planetary care that these technologies also enact. The notion of the 'nexus' enables a situated analysis of the intersection of knowledge, digital infrastructures, and planetary matter, and emphasises the *critical* potential of their rearrangements in both the sense of rethinking and of being problematic. It is not only the planetary, digital, and epistemic components of the nexus that are affected when it is reconfigured, but also other (e.g. ethical) interdependencies.

Pasek and Sutherland interrogate the epistemic virtues of climate-informed machine learning research communities, i.e. the moral commitments of scholarly sub-communities that develop modes of doing research to reduce the carbon footprint of scientific work. The authors underscore that scientists who apply high-performance computing are increasingly concerned about the planetary repercussions of knowledge production through digital infrastructures, and they develop different strategies to 'green' scientific computing. In contrast to the critique that many sustainability interventions are technological fixes, Pasek and Sutherland show how climate-informed scholars address both technical and social domains to green compute-intensive science. It is of interest to this special issue that the compute-intensive sciences attend almost exclusively to energy and carbon emissions as planetary matter – excluding discussions of e.g. minerals, water, biodiversity, mining, labour, supply chains, political economy, and indeed extractivism. Pasek and Sutherland emphasise the need to take seriously the scientists' own internal theories of change and their attempts and strategies of accounting, increasing awareness, and improving technologies. It is a call for joining the critique from within that already exists in the compute-intensive sciences. From the perspective of looking across the layers of data infrastructures, knowledge, and planetary matter, it is furthermore striking that the climate-informed research communities attend to the issue of 'greening' as a technical and social issue, but not as intervening to the knowledge produced. Pasek and Sutherland turn to the 'critique from the margins' exercised by energy humanities scholars when developing methods for doing computing differently, i.e., through solar protocols and information batteries. Here is a direct link to Tremčinský's discussion of grid-scale battery systems. Contrary to the climate-informed machine learning research communities' approaches, the solar

protocol researchers acknowledge how their technologies also have epistemic consequences. The community of AI sceptics (see e.g. Bender & Hanna, 2025) strives for a related reorientation of scientific practice. Here, scholars reject methods and infrastructures found to be harmful both epistemically and planetarily – in particular, AI infrastructures. Furthermore, Pasek and Sutherland's contribution pushes the notion of planetary matter to also embrace the materials of computing devices by urging their recycling. The authors contribute through an emphasis on the variety of attempts existing within science to rethink and redo the interrelations between knowledge, data infrastructures, and planetary matter.

While Maguire's, Pasek and Sutherland's, and Sørensen et al.'s contributions all study intersections across the layers of knowledge, data infrastructure, and planetary matter in the sciences, Tremčinský and Gjefsen et al. interrogate global tech corporations. Gjefsen et al. analyse the rhetorical visions of sustainability among data centre actors. These are discursive framings that reconcile the surging planetary footprint of digital infrastructure with corporate commitments to sustainability. The authors identify eight such visions: from portrayals of data centres as becoming climate neutral by compensating for their emissions through carbon offsetting to their depiction as obligatory passage points for broader societal sustainability transitions, the so-called 'twin transition' of digitisation and decarbonisation. They discuss how these visions have shifted in response to the AI boom around chatbots. Earlier framings emphasising curtailment and climate neutralisation have given way to newer ones in which sustainability is rendered dependent on continued digital expansion and the centralisation of computing power in hyperscale facilities. Here, we are reminded of how Microsoft in 2020 initiated what they called a 'moonshot commitment' project of zero emissions to becoming carbon negative by 2030. However, because of AI, Microsoft now notes that the moon has unfortunately moved further away from us (Nakagawa, 2025). 'Big Tech' firms, Gjefsen et al. maintain, want to act as primary sources of environmental knowledge (building the data centres that help understand climate science), but largely unaccountable ones at that. They selectively render certain entanglements between digital infrastructures and planetary matter legible while obscuring others. Gjefsen et al. thus contribute to this special issue by showing how the intersections between data infrastructures, knowledge, and planetary relations are made *not* to matter. A 'hot issue' is 'freezing out' (Dandurand et al., 2023). Similar to the scientists in Pasek and Sutherland's study, the planetary matters of energy consumption and carbon emissions dominate corporate reporting and structure the rhetorical visions examined. Gjefsen et al. also point to a broader range of material consequences, e.g. related to water usage, rare earth minerals, global supply chains, and the tech sector's monopolisation of renewable energy. These are dimensions that remain at the margins of corporate discourse precisely because the visions are structured to foreground what is easily offsettable. What is thus produced is a performative 'fog,' the authors argue, rather than genuine transparency over the planetary grounding of digital infrastructure.

Steps ahead for thinking across the layers

The Anthropocene is here to stay, as is the question of how to think and act across the layers of planetary matter, knowledge, and data infrastructures. STS proves most productive when it develops concepts close to concrete empirical phenomena: to human actors who grapple with shifting conditions, adapt their practices, revise their accounts, and sometimes refuse the terms on offer, perhaps in artistic ways, with their own server setup in the backyard; and to non-human actors of hardware, metal, electricity, carbon, and other planetary matter that, yes, matter in the Anthropocene. The contributions assembled here offer such combinations of empirical insights as well as advanced conceptual developments.

We introduced the notion of planetary matter to inquire about unruly and ignored relations of the Anthropocene. This small collection of articles can only be a beginning of inquiry into the interrelation of planetary matter, knowledge, and data infrastructures. The empirical phenomena the articles attend to are neither systematically sampled nor exhaustive yet are nonetheless noteworthy. All articles engage with energy flows,

particularly with electricity, and carbon emissions are also key to their discussions of planetary matter. Metals become planetary matter when recycled by the researchers in Pasek and Sutherland's article, as does the sun. (Bio-)Chemicals – both in terms of lithium-ion and DNA – are explored by Tremčinský and Maguire, while plants and living organisms are investigated by Maguire and Sørensen et al. Planetary matter discussed is 'naturalcultural,' always shaped through human-non-human heterogeneous worlds. Listing some of the planetary matters here that inhabit the special issue shows a tendency towards focusing on matter directly related to data infrastructures. Maguire addresses living organisms because plants, rather than silicon-based technologies, make up the data infrastructure in his study. This contrasts with the infrastructures examined in the other papers. That forms of planetary matter most directly related to data infrastructures are prominently addressed in these contributions seems unsurprising, given that the question at stake concerns how data infrastructures are interrelated with knowledge and planetary matter. However, oceans, and water more generally, soil, habitats, minerals, bacteria, viruses, and other microorganisms as well as animals are among planetary matter that it may be worthwhile attending to in future thoughts across the layers of data infrastructures, planetary matter, and knowledge. There is a danger of thinking of such actors in terms of pre-existing entities, but the contributions assembled here (and the planetarity discussion as such) stress how actors come into being, and how actors are to be situated, including their concerns. In the extended relations of planetary matter, as Sørensen et al. emphasise, it is crucial to attend also to planetary matters that are some steps away from data infrastructures but nonetheless entangled in the relations of knowledge and data infrastructure. The methodological challenge running through the issue is how to move beyond sociotechnical and sociomaterial analysis to also hold the planetary within a single analytical frame. It reveals that in studies of knowledge, the planetary notion pushes towards attending to other empirical phenomena than does the notion of 'sociomaterial.'

As to the empirical phenomena, the five articles point to how accounting and valorisation also play a key role in the interrelation between knowledge, planetary matter, and data infrastructures. Gjefsen et al. and Pasek and Sutherland emphasise the importance both in science and in the so-called Big Tech industry of making planetary repercussions of knowledge infrastructures measurable and accountable in order to engage with them. Tremčinský adds that these particular ways of valorising planetary matter are not just about making such matter visible in general. Instead, it is about endowing it with a marketable form, that is, making it legible within capitalist logics and actionable within capitalist practices. While all papers critique extractivist arrangements of planetary matter, data infrastructures, and knowledge, both in science and in industry, the papers by Gjefsen et al. and Tremčinský make it particularly clear that such arrangements cannot seriously be theorised without attending to political economy and capitalist social forms.

Both Maguire and Gjefsen et al. emphasise that intersections of knowledge, planetary matter, and data infrastructures not only make certain forms visible but also create invisibility. Carbon accounts and offset mechanisms make Big Tech's sustainability promises hard to assess, and scientific innovations discussed in Maguire's contribution make potential harm invisible – and in both cases, they make planetary matter not matter. Tremčinský and Sørensen et al. most explicitly engage with how knowledge takes shape across the layers of knowledge, data infrastructures, and planetary matter. Sørensen et al. take a normative stance and suggest a mode of conceptualising scientific knowledge, which they argue will allow STS to take planetary matter into account in processes of knowledge production, and to acknowledge the planetary matter that is the means of production for science. Tremčinský, on the other hand, points to how particular knowledge practices – partly those critiqued by Sørensen et al. – make extractivist engagement with planetary matter possible in the first place.

What do the papers' empirical cases teach us about relations across the layers, the interrelation itself, the arrangement or organisation of knowledge, planetary matter, and data infra-

structures? Sørensen et al.'s conceptual piece on planetary knowledge takes a strong ontological stance, arguing that scientific knowledge is itself part of planetary relations including digital infrastructure. Tremčinský pursues a related but different direction: planetary matter appears as flows whose fluid character resists capitalist legibility until informational layers render it storable and marketable. Maguire's DNA storage case unsettles the boundary between the biological and the digital, reconfiguring what counts as infrastructure and what counts as matter, while Pasek and Sutherland and Gjefsen et al. underscore how planetary matter is selectively made legible through carbon accounting and visions.

The papers do not only offer empirical insights, they also contribute concepts to think across the layers of knowledge, planetary matter, and data infrastructures. Sørensen et al.'s contribution along with Tremčinský's and Maguire's focuses on the arrangement of the three phenomena in question. Sørensen et al. develop the notion of 'extended relations of one shared world' to conceptualise the variety of planetary matter and data infrastructures that are folded into scientific knowledge. Tremčinský's concept of 'batteries' helps to envision processes of organising knowledge that stop the flow of planetary matter. Maguire emphasises the arrangement of planetary matter, knowledge, and data infrastructures by thinking through the term 'nexus' as a situated heuristic to attend to the effects of this arrangement, also beyond the nexus itself. Pasek and Sutherland apply the notion of 'epistemic virtues' and Gjefsen et al. mobilise the term 'rhetoric visions,' both to provide insights into how different domains (science and the data centre industry respectively) conceptualise and normatively assess the interrelations between knowledge, data infrastructures, and planetary matter.

All these different conceptual moves help avoid researching the planetary as backdrop or context. This remains true even if the pull of that backdrop proves difficult to resist entirely, as when carbon and energy are repeatedly put centre stage while (say) minerals, water, and living biosystems recede from view. Thinking across the layers is therefore a continuous critical and political challenge. The layers of knowledge, infrastructure, and planetary matter are arranged in ways that create different visibilities and invisibilities, agencies and inabilities, ethics and normativities. This special issue offers concepts, cases, and sensitivities for studying knowledge, data infrastructures, and planetary matter together, beyond comparisons that reduce their relations to questions of individual digital consumption.

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Notes

1 All lectures from the workshop are accessible online: https://www.youtube.com/playlist?list=PL8ELaEuAJFSDD_x7B5HGajQlwk9dzZLVq. The workshop as well as the work of the editors of this special issue were part of the Collaborative Research Centre "Virtual Lifeworlds" at the Ruhr University Bochum and funded by German Research Foundation, DFG.

Planetary Knowledge: Shifting from Social to Planetary Studies of Scientific Knowledge

Estrid Sørensen

Ruhr University Bochum, estrid.sorensen@rub.de

Leman Çelik

Ruhr University Bochum

Stefan Laser

Ruhr University Bochum

Abstract

Based on a review of literature on the notion of the planetary, the concept of planetary scientific knowledge is developed. It reframes scientific knowledge as integrally and inherently planetary. While building on the established understanding in Science and Technology Studies (STS) of scientific knowledge as socio-material, the planetary perspective introduces a new conceptualisation of scientific knowledge as extended relations in and through one shared world. The notion of planetary scientific knowledge parts with problematic underpinnings of modern science, from widening metabolic rifts to obscured accountability. Planetary scientific knowledge is transgressive, and in its spherical ontology it grants agency to scientific knowledge to intervene in its own means of production. This implies heterogeneous, changing relations and multiple temporalities. The concept of planetary scientific knowledge thus offers a foundation for a move from social to planetary studies of scientific knowledge.

Keywords: Anthropocene, Capitalism, Decoloniality, Digitisation, Globalisation, Ontology

Introduction

There is a growing concern in science about the Anthropocene, climate change and the state of the planet. At the same time, however, scientific knowledge increasingly relies on material extraction and on growing energy consumption, which add to climate change and negatively affect the state of the planet[1]. This article is motivated by the paradox between the increased concern about climate change and the growing contribution to climate change through science. While universities and funding organisations have started attending to questions of sustainable science, particularly with a view to decreasing their energy costs (e.g. Fissi et al., 2021; Freese et al., 2024; Lannelongue, 2021; Pasek & Sutherland, in this issue; Sen et al., 2021; Woolston, 2024), there is a need for more conceptual discussions of scientific knowledge having planetary repercussions. In this article,

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we develop the concept of 'planetary scientific knowledge,' which, beyond questions of how to save energy in science, recycle and use fewer materials, etc., addresses the consequences of understanding scientific knowledge as a planetary phenomenon.

Our argument builds on STS conceptual frameworks of socio-material knowledge and discusses how the notion of planetary scientific knowledge extends analytic attention beyond social and material entanglements. STS scholars have conceptualised socio-material knowledge in different ways, including in material-semiotic (e.g. Law, 2008), hybrid (e.g. Latour, 1993) and epistemic-ontic manners (Verran, 2001). Also, the ontological turn within STS can be seen as a further development of concepts of socio-material knowledge (e.g. Sørensen, 2007; 2009; Woolgar & Lezaun, 2013). These discussions have qualified and consolidated the idea in STS that knowledge is socio-material. They underline the performative socio-material effects of knowledge, in addition to focusing on how knowledge represents certain phenomena or events. Questions of how scientific knowledge in terms of facts and expertise *about* the planet – such as climate science – comes to have effects on politics and society have been detailed in numerous publications in STS (e.g. Edwards, 2013; Gabrys, 2016; Jasanoff & Martello, 2004; Knox, 2020; Latour, 2018; Sandbach, 1978; Silke et al., 2016; Watts, 2018). In this paper, however, we address the very ontology of scientific knowledge and how to conceptualise it as planetary.

Laboratory studies have famously shown that scientific knowledge is produced through technical and often industrial apparatuses. The concept of planetary knowledge extends this conceptualisation by, first, including the materials involved in producing these apparatuses, which are extracted from the planet. Scientific apparatuses, as well as experiments, scientific equipment and mobility, furthermore, consume energy and matter that are also channelled through planetary processes. Introducing the notion of planetary knowledge does not just add more materials and processes to social studies of scientific knowledge. It is, also, about re-conceptualising scientific knowledge. In this article, we focus attention on the conceptual consequences of understanding scientific knowledge as planetary. We do so through a review of how certain scholars (e.g. Chakrabarty, 2009; Danowski & Viveiros de Castro, 2017; Haraway, 2016; Latour, 2017, 2018; Marx, 1969[1865]; Saitō, 2017; Spivak, 1999, 2003, 2012; Stengers, 2015; Tsing, 2015) have been thinking about the term 'planetary,' and we draw on this review to re-conceptualise scientific knowledge. The contribution, thereby, points to planetary scientific knowledge as characterised by 'extended relations' in and through 'one shared world.'

The characteristic *extended relations* of planetary scientific knowledge imply the transgression of set categories, structures and ontologies; they point to the agency of scientific knowledge to intervene not only in practices, where knowledge circulates, but in scientific knowledge's own means of production. They include attention to the heterogeneous and changing relations across the extended relations of scientific knowledge and they address multiple temporalities. We furthermore develop the characteristic of extended relations of scientific knowledge as unfolding in and through 'one shared world' by arguing that extended relations are rendered spherical rather than expanding flatly on one plane; that the planetary acts through its components; that the extended relations emphasise connectedness and not totality; that processes are always shared somewhere, somehow; and that extended relations have consequences rather than limits.

In what follows, we begin with a section discussing key aspects of STS understandings of scientific knowledge as socio-material. Following this, we review current literature on the notion of the planetary to develop and specify this term to think about scientific knowledge. In a third step, we inquire how the concept of scientific knowledge alters when thought of as planetary, just as we discuss the limitations of the term. The conclusion proposes a move from social studies of scientific knowledge to planetary studies of scientific knowledge and discusses the differences between the two.

Socio-material scientific knowledge in STS

Scientific knowledge is not only mental; it is also social, and material. It is not simply a product of

individual thought or genius inventors; it is produced through social relations, including material apparatuses. These are foundational insights of STS. Bloor (1999: 82) maintains that,

> [l]ike Karl Mannheim before him, and many others since, Merton felt that sociological enquiry into the nature of knowledge was … confined to offering a description of the conditions encouraging or inhibiting the growth of science.

In contrast to Mannheim and Merton, early scholars of STS saw the ability to describe and analyse the 'nature' of knowledge – or indeed its ontology – as being key to the field. This ability is not only a question of analytical skill, but also a moral and political commitment to challenge mentalist, individualist, and idealist understandings of knowledge often encountered in so-called herostories. As Kuhn (1962) had emphasised before Bloor, the study of the 'nature' of scientific knowledge meant that the question of truth, which is a pivotal interest of epistemology, became replaced in social studies of scientific knowledge by the question of which knowledge is successful and prevails over other knowledges. Thus, the question of power entered into the study of scientific knowledge. Different directions were taken in STS concerning the conception of socio-material scientific knowledge. We follow the so-called ontological line, which points to scientific knowledge as inseparable from its socio-material enactment (e.g. Law, 2002; Mol, 2002). Garfinkel, Livingston and Lynch's (1981) conversation analysis of the discovery of the Independent Galilean Pulsar[2] (IGP) was an important early study to emphasise the social, material and practical aspects of scientific knowledge. They showed how the IGP as a material object, the social practice of producing it, and the knowledge of it, became intimately entangled through the process of scientific knowledge production. This study was just one of the many analyses in STS that shaped an understanding of scientific knowledge as inseparable from its material and social process of production. Importantly, the authors state that the knowledge *of* the IGP – not *about* the IGP (Garfinkel et al., 1981: 132–133) – was social and material, construed out of the laboratory activities. This trope indicates that the scientific knowledge produced is not different from the production itself. We shall return to this below when discussing the ontology of scientific knowledge.

The laboratory studies (e.g. Knorr-Cetina, 2003; Latour & Woolgar, 1979; Livingston, 1986; Lynch, 1985; Traweek, 1988) consolidated the groundwork for this new conception of scientific knowledge as practical, social and material, and established ethnography as the method of choice to study scientific knowledge. The methodological intervention towards observing 'science in action' (Latour, 1987) and the accompanying re-conceptualisation of scientific knowledge as ontologically social and material did not only reveal new empirical insights about science, it also opened the 'black box' of science to non-scientists and allowed them to form their own – and often different – perspectives on science, independent of the views of scientists. With the conception of scientific knowledge as socio-materially and practically produced, STS gained a new language to speak about science, which made power not only a question of which scientific knowledge prevails, as discussed above; it also challenged the question of the ownership of scientific knowledge and who is granted the right to speak in the name of science.

After the laboratory studies and the emergence of actor-network theory (ANT) followed controversies in STS and beyond about the ontology of scientific knowledge, i.e., about the nature of existence or being of scientific knowledge, about what knowledge is (cf. Law, 2002). These debates primarily concerned the 'general symmetry principle' (Latour, 1999a) and the question of the agency of non-humans in the production of scientific knowledge.[3] Latour (2005) and Law (2008), among others, emphasised that this principle does not regard humans and things as equal, but enables a methodology to observe the distribution of agency among the heterogeneous components involved in creating scientific knowledge.

Moreover, the approach to scientific knowledge as socio-material points to knowledges in the plural of which scientific knowledge is but one kind (and indeed, in itself heterogeneous and embracing many knowledges (Barry & Born, 2013). Scholars of feminist and post-colonial epistemologies have contributed crucially to

this view of socio-material scientific knowledge. As a leading figure in both feminist and post-colonial STS, Harding (1991, 2011) emphasises how researchers' socially and materially shaped, gendered and racialised standpoints condition the knowledge that can possibly be produced. Mol (2002) turned this into not only a question of a plurality of perspectives, but a matter of the multiplicity of materiality – in her case of the body. She discussed the body as having different socio-material constitutions, while remaining one single body, in and through which these socio-material constitutions come together. Analogous to how Mol theorises the body (and later also theory; see Mol, 2021), we can think of scientific knowledge as consisting of multiple translations of a phenomenon combined into one knowledge. Scientific socio-material knowledge is thus in itself multiple and contains tensions.

Importantly, the concept of scientific knowledge as socio-materially and practically constituted also implies its continuous production and maintenance. New materialist thinking has emphasised this aptly with the notion of 'intra-action.' Barad (2007) shows how material bodies and their norms and deviations are continuously re-done through practical entanglements of bodily action and material apparatus, whereby being, knowing and ethics become inseparable matters, where "[k]nowing is a material practice of engagement as part of the world in its differential becoming" (Barad, 2007: 89).

In summary, we draw on a conception of socio-material scientific knowledge in STS that points to an engagement with the practical ontology of such knowledge; that is, with the way scientific knowledge is enacted in and through socio-mate-

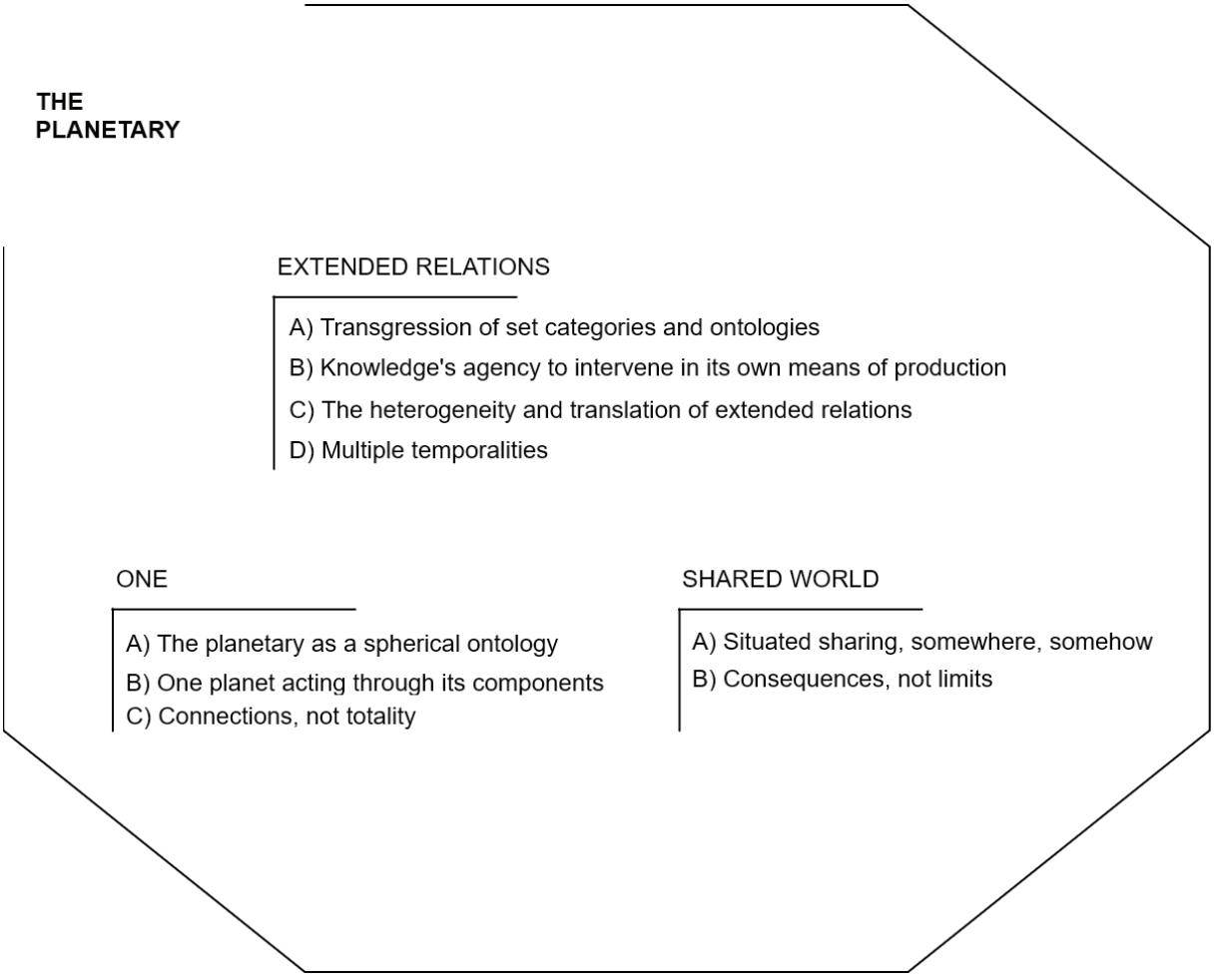

Figure 1 A schematic overview of the concept of the planetary defined as 'extended relations' in and through 'one shared world,' and the key aspects of these two dimensions.

rial practices (cf. Woolgar & Lezaun, 2013). This ontological shift in the conceptualisation of scientific knowledge has had extensive consequences, not only for approaches to the study of scientific knowledge, but also and regarding the societal and political, the local and trans-local status of scientific knowledge, including in STS itself.

The planetary term

In their proposal of a 'planetary turn,' Elias and Moraru (2015) point to a planetary analytic that consists of a conceptual trinity: a) the 'planet' marks a shared ecological habitat and interdependencies of actors and actions near and far; b) 'planetarities' are different modes of performing and living through planetary relations; while c) 'planetarisation' is the ethical practice of making precarious planetary relations visible and discussable. We propose the complementary concept of 'planetary scientific knowledge,' comparable to how STS has developed its understanding of scientific knowledge as ontologically socio-material. Socio-material scientific knowledge is not a specific empirically identifiable kind of scientific knowledge that is different from other kinds of scientific knowledge. Rather, the notion of the socio-material points to a particular conceptualisation of the ontology of scientific knowledge, and accordingly, to specific analytical strategies. Similarly, the 'planetary' serves as an additional specification of both the ontology and analytics of socio-material scientific knowledge.

In what follows, we develop the notion of the planetary as an analytical device that contains the two dimensions 'extended relations' and 'one shared world.' Each of these dimensions is explained below, highlighting their main aspects, as outlined in Figure 1. Our conceptualisation of these two dimensions builds on current literature that explicitly discusses the notion of the planetary as well as on work that engages with related terms, such as the Anthropocene, Capitalocene, Gaia, Chthulucene, and Terrapolis.

Extended relations

The aspect of extended relations of planetary knowledge implies: a) the transgression of set categories, structures and ontologies; b) granting agency to knowledge to intervene in its means of production; c) heterogeneous and changing relations; and d) multiple temporalities.

Transgression of disciplinary categories and ontologies

The first characteristic of the planetary as extended relations is that it implies relations that cross and challenge material and epistemic boundaries, and draws attention to relations that lie between, within and beyond settled categories, structures and practices. Extended planetary relations are partly a result of physical extension. Characteristic to processes and events that are considered planetary, such as climate change or pandemics, however, is that they disrespect pre-defined boundaries, such as geographical, categorical, and ontological ones (cf. Blake & Gilman, 2024): viruses and CO_2 travel across national boundaries regardless of increased border control and environmental regulations; air pollution may be chemical in origin, but quickly transgresses the disciplinary boundaries and turns into social and biological issues (Liboiron, 2021). These examples and the understanding of the planetary term as extended relations draw on post-colonial scholarship pointing to the need to exceed binary Western categories of nature and culture and to rethink multispecies entanglements (e.g. Chakrabarty, 2009; Danowski & Viveiros de Castro, 2017). By foregrounding an incurable 'metabolic rift' already identified by Marx and Engels, ecological socialism highlights how capitalism systematically disrupts the exchange between humans and nature (Burkett & Foster, 2006). The blurring of human-nature boundaries is a deeply material affair, for example when extractivism depletes planetary capacities for reproduction, and due to waste practices that are materially not external to, but integral to, the planetary system (Greeson et al., 2020). The notion of extended relations as an aspect of the planetary notion stresses the inclusion of such processes in planetary analytics. It includes capital's circuits that are inextricably linked with natural processes and bind ecological processes to social inequalities. Tsing and colleagues (2017) revive the metaphor of 'monsters' (cf. Law, 1990) to generate a sensitivity to the 'promiscuous' and heterogeneous entanglements

of extended planetary relations. These are monstrous both in terms of scarring and deteriorating purified modern Western thought and capitalist practices.

Knowledge's agency to intervene in its own means of production

The second characteristic of the planetary as extended relations implies granting scientific knowledge the agency and accountability to intervene in its own means of production. Planetary scientific knowledge's transgressive nature gives knowledge an agency distinct from that assigned in modern technosciences, where scientific knowledge is seen as external to entities within passive environments. The imagined passivity of the object of knowledge and the object's distance to the knowledge that is 'about it' also renders knowledge itself passive. Thus purified (Latour, 1993, 1999b), technoscientific knowledge is considered lacking agency to intervene in the materials, energy and other matters mobilised for its generation.

The agency of human scientists and their intervention in social and biological lives is addressed by scientific ethics, but here, scientific knowledge is acquitted from accountability for how its own means of production and production processes are potentially harmful to planetary relations. The scientific practices' extractive, exploitative and polluting effects are mostly made invisible in the technosciences, and such effects are a priori excluded from their specialised and thus narrow areas of accountability (cf. Liboiron, 2021; Maguire, 2026; Stengers, 2018). This critical research reminds us that the planetary, as an analytical term, must be sensitive towards the agency of scientific knowledge that extends into its means of production.

The heterogeneity and translation of extended relations

The third point about the planetary as extended relations is that the planetary draws attention to scientific knowledge's heterogeneous and changing relations.

Conceptualising planetary scientific knowledge as extended relations differs from ideas of globalised science. Many authors explicitly suggest the notion of the planetary (or similar) as a critique of globalisation, given the specific economic, political, social and indeed anthropocentric rationality of the latter, and its exclusion of non-human agents (Clark & Szerszynski, 2021; Elias & Moraru, 2015). Spivak (2003) famously proposed "the planet to overwrite the globe," criticising that "[g]lobalisation is the imposition of the same system everywhere" (72). We are, she writes, "planetary creatures rather than global entities" (Spivak, 2015: 292). Similarly, Tsing (2004) asserts that the trope of scaling comes with a logic of expansion without changing the frame. We build on these critical engagements with globalisation and scaling and hold that the heterogenous extensions of relations as an aspect of the planetary implies that extension comes with ongoing changes and translations of assembling and disassembling (Greeson et al., 2020; Latour, 1999b). Extensions are furthermore selective – when some relations extend, others are cut (cf. Strathern, 1996).

Multiple temporalities

The fourth characteristic of the planetary in terms of extended relations points to extensions both in space and in time; to the generation of histories and futures; and to both acceleration and slowing down. Many authors point to the planetary as more than spatial. Haraway (2016) defines what she calls 'terrapolis' as an *n*-dimensional space made up not only of the three Euclidean dimensions, but also of stories, memories, practices, multiple species, and more. Several scholars emphasise in particular the temporal quality of extended planetary relations. Developing what they call 'planetary social thought,' Clark and Szerszynski (2021; cf. Hanusch et al., 2021) note that planetary relations continuously change, while Elias and Moraru (2015) emphasise the acceleration of changing relations. Planetary relations do not simply extend in space; they also transform over time. Importantly, the attention to acceleration (cf. Felt, 2025) should not overshadow planetary transitions that are slow, sometimes too slow for humans to grasp (Nixon, 2011). Beyond this processual consideration of the changing and rhythmic character of extended planetary relations, Chakrabarty (2009) and Danowski and Viveiros de Castro (2017) argue

that planetary relations involve history in terms of layers and foldings of historical processes. The problems we must deal with, Danowski and Viveiros de Castro maintain, are not in the future, they are in the past. The authors draw attention to how the Anthropocene – to the surprise and challenge of modern thought – has revealed that the evolution of species and the history of capitalism are deeply interwoven. On the one hand, pasts need to be reconstituted, and on the other, the idea of history as past no longer holds up (if it ever did). Again, Tsing and colleagues (2017) offer a figure to think about extended relations as also temporal: The 'ghost' is a creature from the past that nonetheless has agency in the present.

Conceptually, the planetary also addresses futures. Pels (2015) points to what he calls the 'open future' of modernity, which comes with the idea that any line of development is at any time possible and available to the individual to assess and choose which one to take. In the Anthropocene, future presents itself differently, accompanied by an image of the future of the planet and its inhabitants as in many ways already laid out and considerably constrained. Pels reminds us that key to the generation of the open future was the violent emptying of the American frontier of Native Americans, and that for one future to open up, another may have to be limited, emptied or closed down.

To sum up, the notion of the planetary as extended relations creates sensitivity to boundary-crossing relations extending across categories and ontologies, and it grants knowledge agency to intervene in its own means of production. Furthermore, planetary extended relations draw attention to how relations are heterogeneous and translate as they extend, just as they imply multiple temporalities.

One shared world

Chakrabarty (2009) observes that a human collective has arisen from a shared sense of catastrophe when confronted with climate change. Similarly, Latour (2017) notes that the Anthropocene renders humanity a whole and a single unit. In this section, we critically discuss the planetary as collectifying, unifying or holistic. We bring these thoughts together in the notion of 'one shared world,' addressing first the 'one,' which we explain through three characteristics, and then the 'shared' through two further characteristics (see Figure 1). The 'one' of one shared world is: a) rendered spherical through extended relations bending and turning, not leaving behind what came before, but including it and returning to it; b) the 'one' of the planetary is also defined by the understanding that entities enmeshed with planetary relations – such as scientific knowledge – are not components on the planet, but on the contrary, that the one planet acts through these entities; c) the 'one' of extended relations emphasises connectedness, not totality. The planetary as one 'shared' world additionally points to: a) processes always being shared somewhere, somehow; and to b) consequences rather than limits.

The planetary as spherical ontology

As a first point about the planetary as one shared world we emphasise that extended relations do not expand endlessly on a flat plane, but bend and fold in a spherical space, and return to their point of departure, rendering the planetary 'one.' Different from the flat ontology of actor-network theory (cf. Marston et al., 2005), which generates an image of relations expanding endlessly in all directions, Mol (2021) and Saitō (2017) have recently pointed to the physiological and chemical metaphor of 'metabolism' as a fruitful figure of thought. According to ecological socialism (Burkett & Foster, 2006), Marx adopted the term to think of natural and social processes as an extensive organic whole. He emphasised that the term grants nature a significant position for resisting capital: capital cannot endlessly exploit nature for maximum profit, since while attempting to dominate nature, capital inevitably undermines the foundational material conditions for human – and eventually its own – development. Metabolism is different from the imaginary of a flat ontology of endlessly expanding networks, which never bend, but move ahead, away from its point of departure. It is a circular system in which consequences of action return to their sources, where actions and consequences are of the same process, with digressions and translations included. Excess and spillover are inherent to metabolic circles. The metabolic rift means increased entropy. Bluntly

put, when generated through data practices and run via data centres, scientific knowledge is an extended translated relation of fossil energy, which eventually may undermine the foundation for producing scientific knowledge (cf. Pasquinelli, 2017; Rubio et al., 2025). Thinking with the spherical figure of the planetary term suggests a 'spherical ontology' replacing actor-network theory's flat ontology, and emphasises that any extension will eventually return to its point of departure, which, as discussed above, will however be translated and changed. The spherical ontology renders the planetary 'one.'

One planet acting through its components

The second characteristic of the planetary as 'one' shared world points to all planetary beings as interdependent, and consequently there is no outsourcing, no resort to escape effects of planetary processes nor to act in isolation. Post-colonial thinkers have offered diverse ways of thinking about the planetary as one shared world. Viveiros de Castro (2004) points to universal humanity, which we consider a version of what we call one shared world. He explains that in Amerindian animist cosmology animals are transformations of a primordial universal humanity. Different from a Western cosmology in which humans are transformed animals, animals are transformed humans to Amerindians, and nonetheless still humans. To Amerindians, things and beings generally originate as a transformation of something else – akin to how Westerners think of energy. This cosmology of transformation is another way of conceiving the planetary as one shared world. While this is only one possible way of conceptualising how the planet acts through its components, we take it as inspiration to maintain that the 'one' of the planetary implies that all that is planetary is conjoined – either as metabolic, acting through organisms, or as transformations of a shared universal.

Connections, not totality

The third characteristic of the planetary as 'one' shared world emphasises that the planetary as 'one' implies connectedness, not totality. The conceptualisation of the planetary as one shared world may be misunderstood and associated with the controversial notions of containers (Law, 2015), 'one-worldism' (Young, 2021), holism (cf. Bubandt & Otto, 2010), the 'blue marble' imaginary[4] (Poole, 2008), or totalitarianism (Yusoff, 2018), among others. Critical literature on the concept of the Anthropocene (and Capitalocene, etc.) conveys the argument against a totalising concept of the planetary (Haraway, 2016; Howe & Pandian, 2020; Omura et al., 2021; Tsing et al., 2017).[5] Elias and Moraru (2015: 22) argue sensibly that it is analytically possible – and desirable – to grasp the planet as a whole, while keeping in mind that no "reference t[o] the dynamics of the entire 'world-system'" can afford to lose sight of the complexities, contradictions, and other non-systemic features. Similarly, Latour (2017: 130) formulates the caveat that,

> [w]hether we are dealing with the idea of the Anthropocene, the theory of Gaia, the notion of a historical actor such as Humanity, or Nature taken as a whole, the danger is always the same… [to authorise] a premature leap to a higher level by confusing the figures of connection with those of totality.

Until now, we have focused on the 'one' of one shared world and proposed that the 'one' implies: a) a conception of relations as extending in spherical space; and b) that the planetary acts through its components. We have furthermore c) carefully differentiated between 'one' shared world and totalising singularity. We now move from focussing on the 'one' to the aspect of the 'shared' of one shared world.

Situated sharing somewhere, somehow

The first point about the planetary as a 'shared' world draws attention to multiple, situated planetary processes always shared somewhere, somehow. To 'share' is a curious word that ambiguously suggests that a shared world is made up of various parts that are divided among those who are sharing, and that the shared world at the same time is one common whole.[6] In the sense of one shared world, the planetary is simultaneously whole and divided; it is multiple (cf. Mol, 2002).

Schroer (2022) emphasises the need for a vocabulary of the Earth that involves all living beings and their diverse encounters; not only highlighting cooperation but forcefully including

conflicts. The notion of 'shared' grounds the concept of the planetary by turning the perspective away from imagining extended relations placed in front of perceiving humans and towards a view from inside the relations thus shared. From such a perspective, Danowski and Viveiros de Castro (2017) note that climate change is experienced differently in different places. The sharing of the planetary does not constitute sameness. The planetary as one shared world implies turning thinking away from what Danowski and Viveiros de Castro (2017) call the Western cosmology's discontinuation of nature and culture, which is accompanied by a perspective on the planet as a world before us, a world-without-us, or a peopleless world. Differing from this perspective, the notion of the planetary points to a world-shared-among-us. It is in this context that anthropologists and STS scholars join forces with postcolonial ethnographic endeavours to draw attention to knowledges of Indigenous peoples, and also to experiences of non-human beings. Authors turn to animals, plants, microbes and embodiments of relations "to sound out the elusive depths of the worlds generated in complex, ceaseless, recursive movements between objects and their backgrounds" (Omura et al., 2021: 13). To share the planetary is thus to be situated within the planetary realm, experiencing and engaging particularly – i.e. partially – with a share of the planet. While sharing is often positively connoted, we have been careful to point to damages, conflicts and controversies. Also destruction and violence draw the involved together in relations of sharing – in such cases sharing their destructive or violent relations – although from different and probably opposing positions, possibilities and agencies.

Consequences, not limits

The second point about the planetary as a 'shared' world draws attention to the consequences of shaping shared relations. Spivak (2003) reminds us that sharing always has an object. Sharing means sharing something, which is outside of the one sharing. She calls it alterity: "[t]he planet is a species of alterity, belonging to another system, yet we inhabit it" (Spivak, 2003: 72). The planetary denotes the other to its share-holders, but nonetheless, it is where we live. Like Viveiros de Castro (2004), we emphasise that the collective 'we' of those sharing the planetary will not fully understand it and will not be able to control it; yet 'we' must live in and with the planetary. The situation of being part of a condition of damage and decay, and living with the resources at hand without prospect to progress or extension is described, among others, by Tsing (2015) as living in the ruins of capitalism; by Stengers (2023) as making a living in the ruins; and by Ureta (2021) as 'ruination science.' In addition, Jackson's (2014, 2023) 'broken-world thinking' resonates with this conceptualisation. Broken-world thinking changes the bearing of the planetary. It foregrounds maintenance and creative repair as alternatives or as complementary to a continuous search for new frontiers, new technical solutions or scientific progress that will allegedly solve the crisis. Spivak (2003) adds that being planetary means being 'on loan.' To be planetary is something that has been given to planetary creatures, and it will eventually be given back or taken away.

Ruins, broken worlds and alterity point to constraints. At least since the Club of Rome published their report *The Limits to Growth* (Meadows et al., 1972) – with a terrestrial globe replacing the "o" on the original book cover – the insight that the planetary implies limits has spread widely. Let us contemplate the notion of limits for a moment. A limit is a boundary to expansion, or to a quantity (e.g. of resources). In relation to the planetary, 'limit' emphasises that we can only burn so-and-so much fossil fuel, produce only a certain amount of toxins, work only so-and-so many hours, etc. It places the agent confronted with a limit in relation to that limit, yet external to it. Science-backed environmentalism often claims to identify the remaining limits of specific natural resources or ecosystems' capacities as if they existed 'out there,' say, counting down the minutes until a carbon budget is exhausted. Kallis (2019) cuts into this debate by showing that limits are not naturally given. They arise from social arrangements and the concrete relations of production (and more-than-human metabolisms) through which humans live and work. Liboiron (2021) adds that the very notion of limits stabilises industrial wasting practices by defining seemingly inconse-

quential 'threshold' values and, in turn, destabilises other, more ethical practices.

Haraway's (2016) emphasis on 'living in consequence' as an aspect of 'response-ability' offers a concept to think in other directions than limits. Although they both imply constraints, living in consequence is not the same as having limits. 'Limit' connotes quantity (or lack of quantity) while 'consequence' indicates a register of quality. Hence, limit and consequence evoke different agencies. Limit points to using less; consequence points to responding to the relation in which one is entangled. Importantly, Haraway emphasises that we are not all response-able in the same way. Conceptualising the planetary as sharing does not imply that all hold the same capacities to respond to planetary entanglements. Ecological interventions pose issues of justice, as among others Papadopoulos et al. (2023) emphasise. All planetary creatures share the planetary relations, but we do not all have the same share in the planetary.

In this section, we have discussed how to think about the planetary as 'one shared world,' a conceptualisation that is recognisable in much of STS literature on climate change, the Anthropocene and related issues. We have discussed the reservations and critiques of unifying holistic and totalising understandings of the planetary, and have emphasised an understanding of the 'one' world as a matter of a spherical, relationist thinking and of interdependencies and connectedness. We have finally explained how a 'shared' world is key to the planetary notion in terms of drawing attention to partial and situated processes, and to living in consequence.

Discussion: Planetary scientific knowledge

Above, we outlined how STS has developed a view on scientific knowledge as entangled with diverse socio-material components and processes. This section asks how to understand scientific knowledge if we add 'planetary' to the 'socio-material:' what does it mean that scientific knowledge is planetary? What is the ontology of planetary scientific knowledge? We thus develop a concept of scientific knowledge as planetary by analysing the implications of applying each of the dimensions of the planetary discussed above to the notion of scientific knowledge.

The idea of the planetary term draws attention to extended relations that cross and challenge pre-given boundaries. Applied to scientific knowledge, it suggests that extended relations of planetary matter extracted from the planet – including the efforts of humans, animals, plants, microbes, territories and other planetary matter – are components of and co-constitute scientific knowledge. Planetary scientific knowledge is understood as extended relations not only comprising humans and technologies involved in producing knowledge in academia and in circulating it throughout society, but involving also extractive energy and resource practices upon which the apparatuses of scientific knowledge depend, and which intervene into the constitution of the planet.

Thinking with the notion of the planetary furthermore points to the heterogeneous, translating and multispecies relations of scientific knowledge. Scientific super computers and high-performance and AI computing are good examples. The involved scientific apparatuses are the results of mining and semiconductor fabrication along with global transportation. Scientific competition and its dependency on always faster computing facilities at one location of the extended relations of planetary scientific knowledge is necessarily related to extractive processes of mining, chip production and energy consumption at another location of the scientific knowledge's extended relations, thus intervening in not only social and political orders, but also planetary landscapes and metabolisms. While the computation in the former location may seem harmless and inconsequential, these processes involve extractions and pollution at the latter location, which may leave "scars on the planet, hazardous waste, dangerous and unfair labor practices, ecological devastation, and more," as Hogan et al. (2022: 4) formulate. That scientific knowledge is tangled up with pollution, colonialism, destruction of habitats and violence against more- and other-than-human worlds has already been studied in STS (e.g. Liboiron, 2021). Historians of science have well documented how, already in the early days of modern science, scien-

tific knowledge was already dependent on global supply chains, colonial information orders and scientific knowledge claiming land (and entities residing) to generate knowledge. Schaffer (2009: 247) emphasises that there was "a link between the colonial information order and the empiricist knowledge regime of the late seventeenth century, between forms of epistemology, providentialism and domination." This analytical lens of global capitalism is helpful, too. It points to the capitalist forms of domination involved in scientific knowledge, as well as to the gradual erosion of regenerative capacities folded into these processes. The planetary concept here urges STS to investigate (and potentially challenge) the planet-making activities (Battistoni, 2025) in which scientific knowledge is involved. The notion of planetary scientific knowledge hence means not only understanding scientific knowledge as translated and shaped through socio-material and geo-political processes but also attending to how scientific knowledge is involved in shaping, and sometimes destroying, landscapes and living conditions.

The notion of the planetary emphasises both the spatial extensions of scientific knowledge's planetary relations, and their various temporalities. An illustrative example of how rhythms of scientific knowledge are entangled with planetary temporalities of mineral extraction is the difficult access to (rare) earths during the COVID-19 pandemic, which slowed down the production of computing components (Akcil et al., 2020; Ilankoon et al., 2022; Tooze, 2021). An additional effect was a reduction in the productivity of the sciences that were dependent on the supply of such components (Püttmann and Thomsen, 2024). Shortages in semiconductor supplies, too, delayed the acquisition of 'necessary' computing equipment and impeded data analysis and the progression of experiments in fields reliant on high-performance computing. Geological formations dating millions of years back and resulting in the Atacama Desert being the darkest place on Earth point to another planetary foundation for science, as the desert today serves as the preferred place for astronomic observations. Such planetary pasts are ghosts that actively interact with contemporary scientific knowledge (cf. Burrell, 2020). They underscore the many temporalities of planetary scientific knowledge (Tsing et al., 2017), and they invite STS to rethink the implications of speed, acceleration and slowing down of scientific knowledge (cf. Felt, 2025). The concept of planetary scientific knowledge points to how temporalities and rhythms of the planet are intimately related with those of science.

Learning from scholars of planetary relations, we emphasised the 'one' of the planetary and pointed to a move from flat to spherical ontology. Extended relations do not expand endlessly, but bend in spherical space, making them return to their point of departure. Paraphrasing what ecological socialism states about capital and applying the idea of the entanglement of capital's circulation and metabolisms to scientific knowledge suggests that science cannot arbitrarily exploit nature for seemingly endless progress (Burkett & Foster, 2005; Saitō, 2017; Swyngedouw, 2006). While attempting to know phenomena and processes of the Earth, science may (through its very knowledge-production practices) at the same time contribute to undermining the essential conditions for scientific knowledge. When applied to the understanding of scientific knowledge, a planetary spherical ontology indicates that there is no linear link between planetary conditions for scientific knowledge and scientific knowledge 'itself.' Both are circularly – or spherically – integrated, and they are as much each other's conditions as they are each other's outcome. While the notion of planetary scientific knowledge points to science as consisting of extended relations including both scholarly action in academia as well as mineral extraction, energy production and their related habitats and agents, the 'one' of the planetary emphasises that these relations do not progress endlessly towards infinite horizons. Scientific knowledge and the planet mutually shape each other's conditions and are each other's consequences (cf. Crawford, 2021; Crawford & Joler, 2018; Pasquinelli, 2017) in a spherical space.

The planetary term we developed above furthermore includes interdependency. Planetary scientific knowledge is bound neither to individual human nor non-human agents. The diverse actors that are connected in the extended relations

of scientific knowledge – from scientists, scientific apparatus and organisations to the energy and minerals they use, the mining and fabrication on which they depend and all the processes and practices involved in this – are all entangled with scientific knowledge. We also discussed Viveiros de Castro's (2004) account of Amerindian universality as another version of the aspect of the planetary that we called 'one shared world.' It is worthwhile re-thinking the technoscientific understanding of universality. In planetary terms the universal is not understandings emerging from scientific knowledge; it is the interconnected beings, materials, energies, practices etc., which planetary scientific knowledge both includes and from which it originates as their transformation. Thinking of scientific knowledge as planetary thus means that planetary scientific knowledge is never genuinely new but emerges as ontological reconfigurations of existing interdependent relationships.

An important point of applying the notion of planetary to scientific knowledge, and thus the understanding of scientific knowledge as 'one,' is that its interdependence and interconnection of components imply the multiplicity of scientific knowledge. Planetary scientific knowledge is experienced and unfolds differently in different places, similarly to what Danowski and Viveiros de Castro (2017) write about climate change. Although the product a cleanroom worker helping to etch chips in a semiconductor factory ends up in an HPC cluster at a research centre, it is likely that the worker does not consider their work to be a part of planetary scientific knowledge. The same, of course, is the case for most other human and non-human actors interwoven with the extended relations of planetary scientific knowledge. Pointing to the 'sharing' of planetary scientific knowledge emphasises that the semiconductor worker – along with other human and non-human actors of the extended relations of a certain planetary scientific knowledge – has a share in this knowledge, even if their share receives little or no acknowledgement. Each component of planetary scientific knowledge is situated somewhere, somehow in particular. Each component is akin to the others. Like all other components of the planetary scientific knowledge, a semiconductor worker is involved – probably more intensely involved – in other practices, and other extended relations, which intersect with planetary scientific knowledge and may intervene in its configuration.

Western cosmology's discontinuation of nature and culture underlined by Danowski and Viveiros de Castro (2017) has strong implications for the concept of scientific knowledge. Paraphrasing these authors, knowledge in this cosmology is scientific knowledge-without-us, people-less knowledge. This concept of scientific knowledge as outside the world – and the inside/outside distinction it implies – opens the path wide to extracting living beings and other planetary matter for scientific knowledge. Research shows how the very invention of modern science was achieved through a violent utilisation of nature (Freudenthal & McLaughlin, 2009). The spectrum under discussion is broad and finds various occurrences in modern technoscience, for example in biotechnological interventions that aim to reduce CO_2 emissions, yet primarily advance the capitalist frontier (Folkers & Opitz, 2022). As Burkett and Foster (2006: 137) phrase it while weaving in a quote by Marx: "[c]apitalist industrialisation is a process in which 'science presses natural agencies into the service of labour' (Marx, 1969[1865]: 34) under the pressures of private profit-making and competition." Likewise, decolonial scholars highlight how colonialism shapes modern science by assuming access to land, flattening (Indigenous) relations, and collecting things without attending to situated histories and taking seriously obligations to life in place (Liboiron, 2021; Schiebinger, 2004). Thinking instead in terms of planetary scientific knowledge includes (human and non-human) beings; it includes 'us,' i.e., those sharing the scientific knowledge from within, be it destructive or violent and constructive or collaborative alike.

The final point we discussed in relation to the concept of the planetary above drew attention to sharing in terms of the consequences of being in and of planetary relations. Transferred to scientific knowledge, it means that any of the components and agents of the extended relations of planetary scientific knowledge only engages parts of this knowledge. Moreover, with reference to Viveiros de Castro (2004) we may add that the extended

relations of planetary scientific knowledge are neither comprehensible nor controllable from any location of the extended relations. 'Broken-world thinking' (Jackson, 2014, 2023) and concepts of 'life in ruins' (e.g. Stengers, 2015; Tsing et al., 2017; Ureta, 2021) offer alternative conceptualisations to those of control and comprehension. Different from ideas of science as a matter of heading for new frontiers and scientific progress, these lines of thought suggest conceptualising planetary scientific knowledge not as production, but as ongoing processes of transformation, maintenance and repair.

The extended relations that make up planetary scientific knowledge do not extend endlessly, as discussed above. This is not only because they exist in a spherical space and return to their origins. We emphasise that it is also due to the constraints of the diverse social, material and planetary components making up scientific knowledge. Rather than emphasising the quantitative scarcity and limits of these components, we suggest – based on the reading of the mentioned authors and particularly of Haraway's (2016) work – to think in terms of living with the consequences of planetary scientific knowledge. This is about responding to the extended relations in which planetary scientific knowledge is entangled. Not all actors in the extended relations of planetary scientific knowledge have the same capacity to do so, just as not all profit similarly from the existence and maintenance of planetary scientific knowledge. An important question to address with the notion of planetary scientific knowledge is thus how its actors, communities and controversies shape – and have capacities to shape – spaces and occasions that make it possible to respond to the extended relations of planetary scientific knowledge in which they are entangled. This question also points to the reconfiguration of accountabilities and epistemic justice.

Before concluding our discussion, we would like to draw attention to limitations – or caveats – related to the current state of the notion of planetary scientific knowledge. Thinking in terms of extended relations may inspire a restless methodological drive to move on to the next component of a relation, rather than paying prolonged attention to fewer connections. A way to avoid shallow observations while attending to extended relations may be to engage in team-ethnographic approaches; sharing and distributing scientific agency. The understanding of extended relations may furthermore draw attention to certain empirical objects, and away from others. Energy-intensive, computationally demanding high-tech scientific knowledge and semiconductor extraction for scientific knowledge could be considered more relevant to engage with as planetary scientific knowledge, while neglecting scientific knowledges that sit at the margins of global supply chains of former European colonies, including Indigenous and decolonial knowledges. This is not our intention. The concept of planetary scientific knowledge should urge studies that attend both to the problems of mining-dependent and energy-intensive scientific knowledges as well as to less excessive epistemologies, which may unfold outside Euro-American academia.

Related to this, we have emphasised that not all actors have equal capacity to respond to or shape planetary scientific knowledge. The current state of the concept does not specify where leverage points are, nor how asymmetrical power relations within the extended relations can be contested or redirected. Current critical discussions around AI platforms outside academia, including communities refusing that chatbots are inevitable and pointing to their impact on workers' lives, energy consumption, and polluted rivers and landscapes elsewhere, are examples of increasing pressure against exploitation and extraction. Planetary scientific knowledge's comparable extended relations are rarely discussed in this context. It remains to be specified where potentials for transformation or resistance lie.

The notion of planetary scientific knowledge invokes multiple temporalities – geological pasts, capitalist histories, accelerations and slowing down – yet a deep historicising of these temporalities remains to be worked out. This applies for instance to the connection between colonial information orders and modern computational infrastructure. The concept of planetary scientific knowledge will benefit from more sustained engagement with specific historical trajectories,

emphasising these as more than mere backdrops for contemporary planetary scientific knowledge.

Finally, we have in this article focussed on conceptual development of the notion of planetary scientific knowledge, and although we hope the concept will guide empirical research, we have not unfolded a methodological procedure. We have included a few illustrative examples pointing to materials, energies, mining practices, supply chains, labour conditions, and deep inequalities, yet the practical challenge of tracing these and other empirical phenomena needs to be specified through empirical cases. Research designs based on the notion of planetary scientific knowledge could be ethnographic, discursive, reconstructive, practice analytical, or follow other methodological principles that are particularly well-equipped to combine a multitude of ontologies, sensitive to tensions, ambiguities and partialities, as well as those able to formulate non-reductive accounts. The conceptual framework of planetary scientific knowledge and concrete methodological applications are still to be bridged, and we encourage explorations and tests of the term's empirical relevance and scope.

Conclusion

The shift from thinking of scientific knowledge as socio-material to attending to it as planetary is both a continuation of a strong tradition of conceptualising scientific knowledge in STS, as well as a suggestion of a new conception of scientific knowledge as a component of the planet. With the notion of planetary scientific knowledge, we propose a shift from social studies of scientific knowledge to planetary studies of scientific knowledge (PSSK). Ideas of scientific knowledge as entangled in extended relations – or networks, arrangements or assemblages – are nothing new to STS. However, planetary relations are not explicitly theorised in STS as part of scientific knowledge. Planetary studies of scientific knowledge evoke a different imaginary from the plethora of studies attending to social-material scientific knowledge and its production in and beyond the boundaries of scientific institutions. These emphasise the study of apparatuses, inscription devices, data practices, scientific talk, standards and categories, regulations and politics, scientific cultures and much more. In addition to that, planetary studies of scientific knowledge draw attention to minerals and metals, rare earths, energy and their extractive production processes as also intimately involved in scientific knowledge, although often out of sight to those immediately involved with scientific knowledge. Importantly, more than adding such phenomena into the theorising of planetary scientific knowledge, PSSK imply a conceptualisation of scientific knowledge as extended relations in and through one shared world, as we have outlined above. The boundaries for answering questions of who is granted the right to speak in the name of science are considerably extended when planetary resource entanglements are also acknowledged as being involved in scientific knowledge. Conceptualising planetary relations as constituting and folded into scientific knowledge, PSSK thus urge new constitutions of research sites and new constellations of actors (and alterities, in Spivak's (1999) sense) in studies of scientific knowledge in order to unravel and critically discuss how scientific knowledge through its very ontology contributes to shaping and transforming planetary relations. The notion of planetary scientific knowledge moreover helps draw attention to not only scientific knowledge as planetary, but also to the wealth of literature that attends to this relation.

The move from social studies of scientific knowledge to planetary studies of scientific knowledge is more than a question of scientific insights and academic debate. This article's conceptual development was motivated by concern over science's lack of engagement with its role in shaping the planet. The German National Academy of Sciences Leopoldina published a statement in 2025 critiquing the bureaucratisation of the sciences and its detrimental effects on scientific freedom (Krieg et al., 2025). In its final chapter, the report differentiates between the core tasks and secondary purposes of science and research. Secondary purposes include diversity, justice and environmental issues and, according to the report, such 'science accessorial' (*wissenschaftsakzessorisch*) (Krieg et al., 2025: 18) purposes come at the expense of science's core tasks. The tradition of STS has, as

discussed above, thoroughly documented that gender, culture, and geopolitics are not merely decorative additions to science, but constitutional and inherent dimensions of scientific knowledge. Planetary studies of scientific knowledge in a similar vein draw attention to how planetary processes are indeed ontologically foundational to scientific knowledge and that scholars need to become equipped to attend to the concrete ways in which scientific knowledge has planetary consequences. The Leopoldina report is just one among many contemporary contestations against science and research's attention to planetary relations. PSSK mark a deeply reflexive attempt to draw attention to the planetary consequences of scientific knowledge, which – similar to debates on the freedom of science – encourages reconsideration of science not only as epistemic, social and technical, but as addressing planetary processes that include universities' procurement activities, energy management and science politics, as well as computing, laboratory and building infrastructure, etc., and how thus certain relations are woven and others are cut, with different consequences for the entities entangled based on how the relations are made. This sensitivity points to ourselves, to scholars and scientific institutions, and our interaction with a world that is not only social and, technical, but also and planetary. This ultimately encourages interventions into how actors of scientific knowledge and our institutions respond and adapt to our planetary relations, and can be equipped and create occasions to rework our practices and infrastructures to engage in new and responsible ways with the extended planetary relations of the one shared world we inhabit.

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Notes

1 See e.g. Berné et al. (2022) and Lannelongue and Inouye (2023). Quantifying scientific energy and mineral consumption has particularly been done in relation to computing. This is however complicated and hardly possible to do with precision. Nonetheless, it is not contested that there has been an increased use of computing throughout the younger history of science (Agar, 2006) and of high-performance-computing particularly after the recent simplified access to artificial intelligence applications (e.g. Dongarra and Keyes, 2024). With these developments, more energy, materials and minerals for computer and server parts also become entangled with scientific knowledge practices.

2 The Independent Galilean Pulsar is a highly magnetised rotating neutron star discovered in 1969 at the Steward Observatory, USA.

3 Social Construction of (Science and) Technology (SCOT) emphasised the importance of human interpretation and re-interpretation in the construction of knowledge, just as Collins and Yearley (1992) insisted on the moral primacy of humans and the need to frame knowledge and the social in terms of (human) meaning and intersubjectivity. Actor-Network Theory (ANT), on the other hand, followed the lead of ethnomethodological science studies combined with Greimas' semiotics to point to knowledge as always interweaving both human and non-human actors, and social and material dimensions, resulting in a material-semiotic understanding of science, as Law (2008) characterises this ontology.

4 The 'blue marble' imaginary views the planet from a distance and has, among other things, motivated extractivist space explorations such as Jeff Bezos' recent Blue Origin project (Chaudhary, 2024).

5 The cited authors along with Malm and Hornborg (2014) and many others point to the 'Anthropocene' as an ambiguous figure. It is consummately anthropocentric to name a whole geological epoch after the human, just as the Anthropocene suggests a universalising scope evoking an all-encompassing, authoritative view. However, the term has also proven to inspire arts, activism and critical research, just as it resonates with situated everyday life experiences of discourses and practices of climate change. The survival of the term in these domains after its rejection in 2024 by the International Commission on Stratigraphy only confirms its potential for describing, analysing and navigating contemporary complex planetary lives, not despite, but because of, its ambiguity.

6 See Verran (2001) for further discussions on part-whole ontology.

Battery In/Formation: Modalities of Energy in Transition

Martin Tremčinský

Institute of Sociology of the Czech Academy of Sciences, martin.tremcinsky@soc.cas.cz

Abstract

This article explores how the energy transition is reconfiguring knowledge practices that mediate the relationship between energy and capitalist valuation. It argues that batteries should be understood not only as storage technologies but as information devices that translate intermittent renewable flows into commodifiable forms of energy. Through three case studies – of a virtual battery, Bitcoin-as-battery, and a grid storage battery – the paper identifies three modalities of energy: account, waste, and stock. Each exemplifies how valuation practices (accounting, evaluation, valorisation) abstract energy from its material conditions and render it exchangeable within markets. Batteries thus operate as devices in which planetary energies are re-articulated as economic objects, sustaining the commodification of renewables. The article highlights how the transition to renewables is also a transformation of the knowledge practices that govern energy's circulation.

Keywords: Energy, Information, Valuation, Battery, Bitcoin, Electricity

Introduction

The emergence of capitalism and globalised markets has been closely associated with the combustion of fossil fuels (e.g. Love & Isenhour, 2016; Folkers, 2021). The mobility and flexibility of these fuels allowed for their global distribution and the subsequent statistical calculation and control of energy supplies (Mitchell, 2011). While the combustion of fossil fuels has played a key role in the spread and dominance of Western modernity over the world (e.g. Pomeranz, 2000; Malm, 2016), it also seems to pose a limit to the continuation of capitalist hegemony (Clark & Szerszynski, 2021: 178). The greenhouse gases released by this combustion trap outgoing solar radiation, and the resulting warming is reaching a critical threshold and is raising the demand for alternative forms and sources of energy. In the EU's decarbonisation policies, electricity has been promoted as the central energy carrier, as part of a wider electrification of industry, transport, and buildings. While today electricity consumption accounts for only a little over 20% of Europe's final energy consumption (with oil and gas accounting for most of the remainder), it is estimated that to meet the European Union's decarbonisation quotas by 2050, between 50% and 70% of all energy consumed in the EU would have to be in the form of electricity (Eurelectric, 2024). Furthermore, up to 80%

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is expected to be from intermittent renewable energy sources (RES) (Eurelectric, 2024).

The increase in the use of RES means that energy is increasingly generated only when the wind blows and the sun shines, rather than on demand, in that renewable generation rises and falls with the weather and the seasons (Liang, 2017), which represents a challenge to the business-as-usual model of energy production, distribution, and consumption. One solution to the RES challenge is seen as energy storage. Batteries are ubiquitous; they are used to power mobile phones, computers, cars, houses, factories, and whole towns and city districts. Various forms of batteries are being tested and deployed to capture surplus energy and distribute it more efficiently over time and space. Thomas Turnbull (2024) argued that even the whole earth is one giant battery for solar energy, and that the course of civilisation depends on how this planetary capacity to store solar energy is measured and put to use.

Against this background, this paper asks: *what if batteries were analysed not merely as energy-storing devices but as information technologies?* The question is less far-fetched than it may first appear. Integrating intermittent RES into markets requires that energy be continuously measured, predicted, priced, and accounted for – in short, it requires that flows of energy be doubled by information about those flows. Building on ongoing debates on the relationship between energy and information (Pasquinelli, 2017; Sareen & Müller, 2022; Silvast et al., 2026), I argue that batteries are privileged sites of this doubling: they translate fluctuating flows into informational forms – meter readings, account balances, prices, digital tokens – that render energy knowable, valuable, and exchangeable. Understood as information technologies, batteries thus reveal specific modalities of energy that enable the commodification of intermittent RES and their integration into capitalist energy markets. As such, batteries serve as novel technologies (and techniques) for organising planetary flows of (renewable) energy qua information. The term *modality* names the space of possible and necessary actions that a given medium generates for those operating within it (Degani, 2024), and batteries, I will show, are precisely such media.

Transitioning to RES does not just mean switching the source of energy, as it also requires significant changes in the energy infrastructure. Part of the energy infrastructure – both fossil and decarbonised – is the production and distribution of knowledge in the form of predictable information about energy production and consumption and its circulation across time and space. The dominant mechanism for coordinating production and consumption is the energy market, where the distribution of energy is incentivised through price signals and constrained by the techno-physical limits of the electrical grid (Özden-Schilling, 2024). Storage serves as a tool of price arbitrage. While large producers have long practised such arbitrage through dedicated contracts and markets, storage increasingly allows prosumers (actors who both consume and produce electricity) to react to price signals and withdraw the energy they produce from circulation. Storage thus acts as an economic mechanism that contains complex valuation processes in order to maintain the market and help producers to extract surplus value from commodities (Orenstein, 2019; Simpson, 2019).

This paper demonstrates how batteries, in their various forms, serve as one of these valuation mechanisms that generate different modalities of energy from intermittent energy sources and thereby shape the relationship between the physical world (as a source of energy) and the practices that render it economically knowable (as information). I use these terms in a deliberately non-technical sense: energy for the physical capacity to do work, information for its representation in measures and prices, and knowledge as the effect of information and energy contained within social networks and human bodies (Mirowski & Nik-Khah, 2017). The paper starts from the proposition that "[w]e understand electricity not as a source of energy but as a means for transferring power over space and time, a kind of currency" and further explores how "*the generalisation of [batteries'] form*, [has resulted in] a kind of terrestrial accountancy" (Turnbull, 2024: 650, emphasis added). In other words, storing and transferring electricity across time and space is

not a neutral technical operation but a political process: it requires that flows of energy be continuously measured and recorded, and the resulting information – meter readings, account balances, price signals – feeds into the coordination of the global capitalist economy. Batteries are therefore approached here not as mere physical devices but as elements of planetary knowledge infrastructures: devices in and around which information about energy is produced and organised, and through which that information is turned into economically actionable knowledge.

The setup of the paper is interdisciplinary in its sources, but its intended contribution is to STS – specifically to debates on valuation and on the digitalisation of energy (Çalışkan & Callon, 2010; Vatin, 2013; Helgesson & Muniesa, 2013; Özden-Schilling, 2021; Sareen & Müller, 2022; Silvast et al., 2026). Offering an empirically grounded conceptual analysis (Jensen, 2013), it mobilises two further bodies of work in a supporting role. From the history and critique of economic thought it takes the price-as-information nexus: Hayek's (1945) essay is engaged not as a distinct theoretical authority but as a paradigmatic primary statement of the much broader (neo)classical discussion of valuation via equilibrium market prices, whose trajectory has been reconstructed by Mirowski and Nik-Khah (2017; see also Beckert & Aspers, 2011) – and as a statement that, as I show below, also informed the design of one of the devices studied here. From the political economy of information, it takes Pasquinelli's (2017; 2022) historical account of energy and information as entangled metrics of industrial capitalism, which allows me to frame information as the economic intelligence of energy. The analytical work, however, is done with the toolkit of economic STS and valuation studies – objectification (Çalışkan and Callon, 2010), evaluation and valorisation (Vatin, 2013), and enactment (Mol, 2002) – applied to empirical material from the Czech energy transition.

Empirical base

The empirical basis of this paper stems from my ongoing research on the digitalisation of energy in the Czech Republic and the role of various storage technologies in this process. The paper draws on three case studies of multiple batteries: a virtual battery, Bitcoin-as-battery, and a grid-scale battery. In these cases, batteries serve not only as technological devices but also as powerful analogies – that is, devices that are not literally batteries but perform a battery-like function of reallocating energy – for various energy-utilising practices. Only one of the case studies – the grid-scale battery – is a battery in the technical sense of the word, i.e., a storage device for energy. The other two – the virtual battery and Bitcoin-as-battery – are analogies for knowledge practices that utilise and commodify intermittent electricity from RES.

All these cases are, on the one hand, articulated by various actors in the energy market, such as electricity providers, their customers, various professional associations, commentators, and opinion makers. All these actors enact various batteries through their products and services, market behaviour, and media outputs.

On the other hand, I assemble the cases, and my focus is on batteries as information devices; this is why I concentrate on these specific types of batteries rather than others. The empirical material was gathered in two steps. First, I conducted a podcast-based ethnography (Lundström & Lundström, 2021) of the Czech energy transition. The podcasts were selected thematically: from the growing Czech podcast production on energy, I chose series and episodes in which batteries and energy storage are explicit topics. The resulting corpus comprises over 35 hours of interviews produced by a range of stakeholders, from the association of battery producers and users, through public service broadcasting, to non-governmental organisations. I treated these podcasts as ethnographic field sites (Lundström & Lundström, 2021): I listened to them repeatedly, took notes, and annotated recurring actors, products, arguments, and controversies, which allowed me to orient myself within the Czech space of battery producers, sellers, and users. Second, following the actors and products encountered in the podcasts, I assembled a complementary corpus of texts – websites, promotional booklets, press articles, and expert commentary – likewise selected thematically for their discussion of various batteries (see Ortner, 2010) on studying

up through publicly produced materials. In the case studies below, the podcast corpus serves primarily to map the field, to identify the actors and products analysed, and to supply expert framings. This approach focuses on empirical material produced at the interfaces between energy infrastructures, markets, and expert publics, and treats this material as emerging from situated knowledge practices through which the energy transition is narrated, problematised, and rendered economically legible.

The assembled cases serve as exemplars of three modalities of energy in the current energy transition: account, waste, and stock. Analytically, the moments of valuation come first: it is the practices of accounting, evaluation, and valorisation that enact energy in these modalities. Each case has therefore been selected to foreground one moment of valuation and the modality of energy it enacts. The identified modalities of energy are not exclusive to these cases. Energy is enacted as an account, for instance, in net-metering and feed-in-tariff schemes across Europe; as waste in the curtailment of renewable generation and in the flaring of associated gas at oil wells – a surplus recently captured by Bitcoin miners (Carter, 2021); and as stock in strategic petroleum reserves, natural gas storage, and pumped-hydro plants (Simpson, 2019). Nor are these the only modalities that can be identified in the current energy transition (see Sarrica et al., 2016; Silvast et al., 2013).

Information as the valuation of energy

The history of industrial civilisation, according to Matteo Pasquinelli, is driven by two entangled forces that he depicts as a 'two-headed chimera', with one head bearing the name of 'energy' and the other that of 'information' (Pasquinelli, 2017: 311–312). Both entered industrial production at roughly the same time, with the introduction of Watt's steam governor and Jacquard's punched cards: energy as the medium of motion, information as the medium of communication and control (Pasquinelli, 2017: 316). In his later work, Pasquinelli (2022: 4) treats energy and information as metrics, understanding such metrics in general as ''systems for quantifying nature, labour, productivity, and social praxis'' and analysing the way they have historically been spaces for the negotiation of social conflicts. Extending this observation beyond Pasquinelli's account, it can be added that, on the basis of such metrics, Western culture has become accustomed to comparing or even hierarchising human societies according to their ability to harness energy and record information (White, 1943; Assmann, 2011), whether through the use of combustion or of writing and recording, or through the ways human societies deal with an excess of energy and information, ranging from human sacrifice to biotechnology (Bataille, 1988; Thacker, 2005).

Turning from these historical configurations to the practical register – and following Cara Daggett's (2019: 70) genealogy of energy – energy is generally defined as the ability to perform work. The modern thermodynamic concept of energy rests on measurement, and it is this measurability that made energy available to control and, eventually, to commodification: "energy provided a unit of equivalence that was legible to human accounting and surveillance techniques" (Daggett, 2019: 48).[1] Once energy can be abstracted from the relations of its existence as a measurable unit – both materially and conceptually – it can be controlled, accounted for, and marketised. Through this series of abstractions, socially and environmentally embedded energy becomes an alienable commodity.

The availability of energy depends on the distribution and availability of potential resources (ranging from the gravitational pull of planetary bodies and solar energy to human and non-human bodies and fossil fuels). Neo-classical economists propose that, at least in theory, the use of resources – and thus of energy – should be organised according to the demand and supply equilibrium provided by the free market (Solow, 1974: 7). This equilibrium, however, depends also on the distribution of knowledge that manifests supply and demand in the form of price signals. A canonical statement of the connection between information and markets was formulated by Friedrich von Hayek (1945). Hayek's problem was that of rational economic order under conditions of dispersed knowledge:

because the knowledge of particular demand for limited goods is scattered among countless actors, it can never be given to a single mind or planner. His solution is the price system: the price of a good condenses the dispersed knowledge of its relative scarcity into a single signal, allowing actors to coordinate their plans without knowing anything beyond the prices of the goods that concern them. For Hayek (1945: 525), prices thus represent "indices (or 'values') in which all the relevant information is concentrated." For Hayek, the mutual interactions of information as prices within the market create new form of transindividual knowledge that cannot be possessed by any single person (Mirowski & Nik-Khah, 2017). The market – including the energy market – is thus in this paradigm perceived as a source of knowledge that informs the production, distribution, and consumption of material resources.

Hayek's system of decentralised distribution based on market prices relies heavily on the practice of *valuation*, whereby values are assigned to goods and commodities so that these can be compared to each other and subjected to rational calculations. In Hayek's theory, the space of valuation is the market, where commodities are compared to each other and their value, in the form of a price, is the outcome of these comparisons. Contrary to Hayek, François Vatin (2013: 38) argues that valuation cannot be fully carried out in the market, noting "[t]he market price doesn't freely invent itself on the market as standard economic theory would have us believe". Instead, Vatin (2013: 38) argues that production also participates in the valuation process of a commodity, since "exploring work as an activity producing measurements is to explore its producing value and valuations" and therefore "goods and workers arrive on the market already calibrated, classified, and measured in many ways". Every market thus depends on a variety of factors that remain black boxed as mere problems of technology (Vatin, 2013: 41), so the market can act *as if* goods were valued according to market equilibrium. 'Black boxing' is used here in the STS sense of rendering the internal workings of a practice or device invisible, so that only its inputs and outputs remain in view (Latour, 1987). It thus denotes something different from economisation and marketisation, which designate the broader processes through which entities are constituted as economic and marketable (Çalışkan & Callon, 2010), and from valuation, which refers to the practices through which worth is attributed and augmented (Vatin, 2013). In the cases analysed below, batteries black box valuation: they package practices of accounting, evaluation, and valorisation into devices whose output – storable, priced energy – appears as a simple technical fact.

To treat valuation as independent from production and dependent on exchange assumes, among other things, the durability and storability of the exchanged goods. Where there are limited means of storage, production immediately also becomes a direct problem of valuation (see e.g. Asdal & Cointe, 2021; Banoub & Martin, 2020). Valuation and production are bound together, as information evaluates the availability, distribution, and use of energy to be put to work in production.

Information on the availability of potential energy sources thus "emerge[s] like the late twin of computational capitalism, in which computation appears to be oriented to the calculus of the planet's *surplus energy* rather than the calculus of *surplus labour*" (Pasquinelli, 2017: 320, emphasis in the original). The dominant metaphor for this process has come to be a *metabolism,* interpreted as *thermodynamic accounting* (Daggett, 2019: 116). This thermodynamic accounting supports a whole mechanical ontology, "which corresponds remarkably well with capitalist rationality via the [quantification] of capital in its monetary and productivist forms (currency units, units of labor-power, etc.)" (Moore, 2017: 295). The point is not that energy comes to be described in numbers, but that energy becomes an economic object only once it is rendered calculable and consequently controllable via information. Therefore, Pasquinelli argues that "*information is the economic intelligence of energy*" (2017: 313, emphasis added).[2] This process came to be due to the emergence of the fossil economy: "the abstract properties of information emerged thanks to the nature of fossil energy, to its homogeneous carbon chains, that made coal easier to quantify and compute than traditional sources, such as water or animal power" (Pasquinelli, 2017: 316). I aim to demonstrate, as I elaborate my argument further, that

the battery is a new manifestation of the economic intelligence of fossil capitalism applied to the post-carbon economy.

In this perspective, information abstracts energy from the conditions of its existence, which allows energy to be *objectified* and subsequently commodified and marketised. Koray Çalışkan and Michel Callon (2010: 5-6) argue that "objectification work (quite literally the work of making objects) must be done to disentangle things from their networks of connections" and thus "transform[s] entities from entangled beings into passive things". The practices of measuring and standardising then further solidify the disentanglement of objectified commodities. "Disentanglement is more stable (that is, less vulnerable to the constant pull of re-entanglement) when a commodity has undergone specific processes of standardisation that transform it into an entity described in both abstract and precise terms" (Çalışkan & Callon, 2010: 7-8). The objectification – and consequently commodification – of energy results from the knowledge practices of valuation, such as measurement, accounting, and management.

The valuation and modalities of energy

Vatin's intervention belongs to a broader field of STS-inflected valuation studies that treats value not as a substance but as the outcome of practices of valuing (Muniesa, 2011; Helgesson & Muniesa, 2013; Kjellberg et al., 2013; Doganova et al., 2014; Dussauge et al., 2015). Within this field, I draw specifically on Vatin (2013) because his distinction between evaluation and valorisation provides the processual vocabulary that the analysis below extends with a third moment, accounting.

Vatin (2013) contrasts valuation with static value and describes it as a dynamic process. In his view, valuation consists of two interrelated moments: *evaluation* and *valorisation*.[3] I suggest adding *accounting* as another moment of this process.

Evaluation means assigning value to a commodity, while valorisation is understood as increasing the value of a commodity: "'to evaluate' (évaluer) corresponds with a static judgment attributing a value to a good, a thing, a person; on the other hand 'to valorise' (*valoriser*) has a dynamic meaning – increasing a value, adding an increment to it, a surplus value" (Vatin, 2013: 33). Neither evaluation nor valorisation is self-evident: for an increment to be recognised as an increment, a prior evaluation must have been registered in a form stable enough to be compared with a later one. Accounting is precisely such a registration: it converts shifts in valued qualities into quantities that can be compared. It renders heterogeneous evaluations commensurable and circulates them as information about economic reality. Rob Bryer (2006: 552) thus describes accounting as, "the 'totality' of the control process because it provides an objective framework within which all other control systems and realities are subsidiary and subservient". It is a crucial process in the control of production that distributes information about economic reality. Accounting, evaluation, and valorisation therefore cannot be understood as bricks stacked on top of each other; a more accurate visual metaphor would be a closed loop. Accounting needs to be informed by evaluations in order to produce new evaluations; valorisation creates evaluations that are consequently valorised again.

The valuation of energy is thus a set of knowledge practices (accounting, evaluation, and valorisation) that abstract energy and allow its objectification and, consequently, its commodification. However, these practices do not happen solely in the marketplace, as they depend also on the devices that enable the transformation of energy so that it can *enter* the marketplace (Özden-Schilling, 2021).

Throughout, I use *modality of energy* to name the particular form in which energy is made to exist and circulate within a socio-technical assemblage – the way it is rendered knowable, valuable, and exchangeable. Following work on the enactment of objects in practice (Mol, 2002), a modality is not an intrinsic property of energy but something done to it: energy is enacted e.g. as a flow, a stock, an account, or waste through the very valuation practices set out above. Each modality is in this sense the correlate of a valuation moment – accounting, evaluation, or valorisation.

This enactment-based account can be deepened by recent anthropological theorisations of modality itself. Degani (2024: 60–61) proposes a *modal anthropology* concerned with what is possible and necessary for actors operating within a given technical, aesthetic, or ecological medium. In this framework, a mode is a virtual possibility space: like the grammatical modals *may* and *must*, it designates the actions an actor can, should, or cannot take, whether or not those actions are actualised. The constraints and affordances that generate such spaces of possibility are in turn conceptualised as *media* – protocols, equipment, infrastructures, social statuses, or bodies; anything that channels an actor's capacity to act (Degani, 2024: 61). The battery is a medium in exactly this sense. Degani's (2024: 73) own example is instructive: once a household possesses a connection to the electrical grid, it is elevated into a new possibility space of rights and responsibilities – of 'mays and musts' – in relation to the utility and, ultimately, the state. The batteries analysed below perform the same modal work for renewable energy: each generates a distinct possibility space that defines what its users may and must do with intermittent electricity. A modality of energy, then, is at once an enactment (Mol, 2002) and a possibility space (Degani, 2024): the form in which energy is made to exist, and the horizon of possible and necessary actions that this form opens up for – and imposes upon – those who handle it.

Given the socio-physical properties of the whole electricity assemblage, the dominant modality of electricity up to now has been the *flow* (Özden-Schilling, 2021: 11), while the modality of fossil fuels has been the *stock* (Jevons, 1866; Simpson, 2019). This modality co-emerged with the valuation practices of centralised electrical grids, which were organised around regulated energy sources such as fossil-fuel power plants. The regulation – and hence also the valuation – of the flow of electricity has been achieved both directly, by regulating the throughput of the grid (the flow), and indirectly, by modulating the input of fuel (the stock).

Since the physical properties of energy drawn from renewable sources of energy do not allow for any effective control of the source of energy itself, one of the valuating devices deployed in the renewable energy market is the battery. The battery serves as a valuation device that "opens opportunities for arbitrage by maintaining electricity in a state of potential, ready for use or exchange" (White-Nockleby, 2022: 699).

The use of batteries in valuation, however, also implies that other modalities of electrical energy, in addition to/other than flow, come into play. In the following section, I identify three such modalities – account, waste, and stock – each exemplified by a different type of battery: a virtual battery, Bitcoin-as-battery, and a grid-scale battery. These modalities correspond to the three moments of valuation: accounting, evaluation, and valorisation. The three modalities are not exclusive to the three types of batteries; they serve as heuristic categories that are used to demonstrate different valuation practices within the process of the commodification of energy from RES. Methodologically, this design corresponds to what Degani (2024: 64–65) terms *cross-modal* comparison: rather than comparing modes in the abstract, it holds a single worldly operation constant – here, valuating the surplus renewable electricity – and examines how that operation is differently configured, with different costs and beneficiaries, in each mode.

Virtual battery: accounting debits and credits

The first case shows the valuation moment of accounting. In this case, electricity is not stored materially but rendered into credits and debits, allowing distributors to abstract energy as an account. This case demonstrates how batteries, even when only simulated, function as valuation devices that transform flows of electricity into legible economic units.

The virtual battery is a product offered by two major Czech distributors of electricity, namely E.ON and ČEZ. The general model is based on net energy metering, where the client, equipped with RES (such as photovoltaics) and a smart-meter device, becomes a prosumer, both producing and consuming electricity. The valuation of electricity in the case of a virtual battery depends on quantification. Quantifying electricity via metering is a peculiar process, since electricity "is contained

within the wires and cables of an electrical network, but its quantity and flow do not directly display themselves" (Kragh-Furbo & Walker, 2018: 1). Electricity metering is thus a complex process that is required in order to "establish the basis of an exchange value between supplier and customer" (Kragh-Furbo & Walker, 2018: 3). Historical developments in electricity metering caused electricity to be "further abstracted [...], translated into information that is seen to demand action rather than understanding" (Kragh-Furbo & Walker, 2018: 6). Electricity metering can thus be interpreted as a form of accounting that is generally understood as a distribution of information with a "capacity to influence and mobilise, to fundamentally affect decision-making" (Power et al., 2003: 132). In the case of the virtual battery, this ambiguity can prove to be a double-edged sword.

The general assumption behind the virtual battery is that the prosumer cannot always produce and consume energy at the same time. Given the specific nature of the electricity grid, the produced electricity has to be consumed immediately. If the prosumer is not able to consume their product, they have to either stop producing or let the energy overflow into the grid, where it will be consumed by some other party. The virtual battery is supposed to provide an alternative solution. When a prosumer produces more energy than they consume, they can 'store' their energy in the grid to consume it later.

> The virtual battery works in the same way as a physical battery. However, instead of a battery, a distribution network is used directly to store energy. Practically, everything runs so that unused electricity from your home solar power plant is fed back into the grid to be used by whoever needs it. Your smart meter measures precisely how much electricity is sent, and you can take the same amount back from the grid later. All you pay is a distribution fee, which is paid whenever you use the grid.[4] (E.ON, n.d.)

Despite claiming that the virtual battery works as a 'physical battery', E.ON also identifies some differences. Mainly, unlike a physical battery, the virtual battery has in theory unlimited capacity:

> The difference is that while you can only store a limited amount of energy in [...] a physical battery, with a virtual battery you are not limited in this way and can use the excess energy at any time later. (E.ON, n.d.)

One of the providers of photovoltaics, a company called Ilios, acknowledges that this is a metaphor. The energy cannot be stored in the grid; it has to be consumed instantly.

> But it's not nearly as straightforward as it may sound. The supplier can't just dump your energy into the grid; instead, it finds a customer [that will consume it]. Once you decide you want to use your energy, the supplier has to find a seller and buy it for you. (Ilios, n.d.)

Various experts on energy and accounting have therefore described the virtual battery as an *accounting trick*. The energy sent into the grid is accounted for and the prosumer can later withdraw from the grid the same amount that they previously deposited. The virtual battery thus utilises the accounting logic of double-entry bookkeeping, where the sent energy is recorded as credits on the side of the producer and debits on the side of the distributor. The other Czech distributor that provides this service, ČEZ, has acknowledged that the ''surplus electricity goes to the distribution network, but [the clients] are essentially *trading* it'' (ČEZ, 2023, emphasis added). This also means that, in the case of the virtual battery, the energy is produced twice: once when it is credited, and once when it is debited. Information here serves as a metric of the work that has to be carried out in order to clear the account.

The clearing of accounts is a highly asymmetrical process, because if prosumers produce less energy than they consume, they have to buy the rest from their distributor. However, if they produce *more* than they consume, the surplus is not compensated in any way. The distributor gets it for free, so even if the price of energy is low, the distributor profits from trading it. The amount of credit prosumers can accumulate is limited by their ability to produce surplus energy, while their ability to consume energy represents a limit on the debits they can collect from their account.

For the distributor, the only limit is the physical capacity of the grid.

Criticism of this system has deemed it economically irrational because the distributor charges the prosumer a flat rate fee and in order for the prosumer to break even the amounts of electricity both sent and consumed would have to be quite large (Matajs, 2024). However, if the quantity of energy produced increases, the flat rate fee charged by the distributor might significantly increase as well and make the virtual battery unprofitable. The accounting of the virtual battery is counterintuitive, and it obfuscates certain costs related to its operation. Unlike standard energy pricing, in this case the energy is not priced directly according to the amount consumed, and instead debits and credits are accounted for in kind as one megawatt hour for one megawatt hour. Therefore, unlike in standard capitalist accounting, where money serves as "a common denominator [used] to calculate an overall measure of performance" (Bryer, 2006: 564), here the energy assumes the form of an accounting currency, circulating between the distributor and the prosumer. The flat rate fee is paid to the distributor not for consumption but for the management of the account. The energy is thus not evaluated as a commodity with a price; it is traded in volumes of energy.

However, while distributors aim to obfuscate the costs by measuring and exchanging quantified energy, prosumers calculate all their costs, including the distribution fees or amortisation of their equipment, and then compare them in online forums.[5] The calculations provided by some members of the forum clearly show that the virtual battery is only profitable under very narrow circumstances.

Accounting thus serves both sides, the prosumers and the distributors, as a means of control. For Bryer (2006), the information obtained from accounting is used by distributors to control the production process and thus also the workers employed within it. In the case of energy prosumers, accounting holds them accountable for the production of the energy they provide to the grid. If the amount of energy provided to the grid reaches the upper limit set by the distributor, the flat rate fee is increased. If the prosumer does not collect enough credit in their battery, the cumulative price of energy is higher than it would be without the virtual battery. To paraphrase Bryer (2006: 567), "the [prosumer] must look not simply at the total circuit of capital [i.e. electricity] through [energy] accounts, but must look deep into production by means of management accounts". Accounting thus serves as a form of control and exploitation of the prosumers by the distributor. Nevertheless, it also gives the prosumer commensurable tools with which to evaluate the product of the virtual battery and potentially reject it.

In summary, the virtual battery depends on the measurement of electric energy and its translation into accounting information. The modality of energy as an account underwrites the process of real abstraction in which two commensurable volumes of energy can be exchanged at different times as identical equivalents despite coming from different sources. The use of accounting also implies possible conflicts since it partially obfuscates the costs associated with the product sold to individual prosumers. The prosumers can then challenge the distributors' accounting with their own calculations. These calculations depend not only on the ways in which energy is accounted for but also on how it is evaluated. In the case of a virtual battery, the evaluation of energy is obscured to prevent the real costs from being calculated. However, prosumers evaluate their energy anyway by calculating the prices of energy and their own equipment.

Bitcoin-as-battery: evaluating waste

Bitcoin, which is itself an accounting system (Fortin & Pimentel, 2024), has been promoted by its proponents as a battery that can accumulate surplus energy in the form of unique information. The process of so-called *Bitcoin mining* rests on energy being spent on – or rather sacrificed for – computational labour that records unique inputs and outputs of data in a shared ledger of accounts called a blockchain. The design of the blockchain is to prevent attackers and other dishonest actors from corrupting the system by rewriting the transaction history and to incentivise honest (non-malicious) mining.

The computational labour of Bitcoin mining is carried out by special computers designed solely

for this purpose. These computers perform a specific cryptographic function — the SHA-256 hash function — until they find a solution within a set range, and the labour is rewarded with newly emitted bitcoins. These bitcoins statistically belong to the actor who utilised their energy most effectively, in terms of the ratio of computational power to energy spent. Mining is thus a competitive race in which any efficiency gain by one miner drives the others to catch up, inevitably raising the energy demanded by the network as a whole. Since mining is energetically highly demanding, miners permanently seek new sources of cheap energy, and surplus energy from renewable sources is one such opportunity. Chinese Bitcoin miners, for example, used to migrate seasonally (prior to the Chinese ban on mining in 2021) to exploit the surplus from hydroelectric plants during the monsoon season (Redman, 2019).

The competitive design of Bitcoin mining increases energy consumption over time. Whereas initially Bitcoin mining was carried out on laptops and PCs, today it takes place in warehouses filled with special hardware and run by either individual miners or private companies renting their computational capacity to international investors. The increase in energy consumed by global mining operations was more than significant: It is estimated that the energy consumption increased from one terawatt hour (TWh) per year in 2013 to over 120 TWh per year in 2023 (Cambridge Bitcoin Electricity Consumption Index, 2024).[6]

Also, the competitive design of Bitcoin mining means that only the energy spent by the winning miner, who was able to add their block to the blockchain, is utilised. The energy spent by other miners is not transformed into a record in the blockchain. However, the total energy spent in the mining process serves to adjust the difficulty of mining (the range of acceptable solutions of the SHA-256 function), so if there is an increase in computational power, the emission of new bitcoins keeps a stable pace.

The energy spent on Bitcoin mining is not just transformed into bitcoins. Since most of the energy has no impact on the network other than it being consumed, it would be more precise to say that this energy is *sacrificed*. One of the early members of the Bitcoin forum described this as "a 'thermodynamic burden' that the currency has to carry" (Champagne, 2014: 235). The consumed energy is supposed to add to the network's security because the energy sacrificed by a potential attacker would have to be greater than the sum of energy sacrificed by the honest miners for it to be successful. The rationale behind this operation is that it is more effective to use the energy for honest mining than for attacking the network. Therefore, most of the energy spent on mining is sacrificed to discourage potential attackers from using their own resources to rewrite the shared ledger. The competition, therefore, is between agents capable of sacrificing the most energy the most effectively at the altar of the system's durability (cf. Bataille, 1988). Information becomes – via computational labour – the objectification of the sacrificed energy.

The constant search for cheap energy and the subsequent utilisation of surplus energy from RES gave rise to the analogy of Bitcoin as a battery. In the Czech media, the imaginary of Bitcoin-as-battery has been articulated on multiple occasions by a variety of actors. Tomáš Havránek – a former advisor to the Deputy Governor of the Czech National Bank, Mojmír Hampl – addressed this issue in a news survey exploring the future of Bitcoin.

> A couple of years ago, Mojmir Hampl and I were thinking about the best use of cryptocurrencies. We came up with the idea that they work well as batteries: if you have solar panels on your roof, a standard battery of sufficient capacity is expensive. If you don't have a battery and sell the unused electricity to the grid, you make pennies. The solution is to mine bitcoins or other cryptocurrencies during the day with the excess electricity. You can sell them in the evening and use the money to buy electricity at night. A Bitcoin makes a battery of unlimited capacity. (Kubita, 2021)

This statement was based on an article Havránek co-authored with Hampl, which was also published on the official website of the Czech National Bank (Hampl & Havránek, 2021). In this article, the authors criticise cryptocurrencies from the standpoint of modern money. According to this theory, modern money functions simultaneously

as a store of value, a currency in circulation, and a unit of account.[7] Havránek and Hampl argue that Bitcoin does not convincingly meet any of these characteristics and thus must be treated as something other than money, namely as a commodity. ''Cryptocurrencies were created as 'digital commodities' and must therefore be treated like traditional commodities: gas, tin, or corn'' (Hampl & Havránek, 2021). According to Hampl and Havránek, the best use of Bitcoin is, therefore, to 'store' cheap energy by transforming it into a digital commodity.

Another proposition of Bitcoin-as-battery was formulated by Alex Pilař, a former global manager at the logistics company DHL, who argued that storing energy in Bitcoin represents the ultimate argument in favour of Bitcoin's sustainability:

> The thesis that Bitcoin destroys energy is a myth. We know from primary school that energy cannot be destroyed, only transformed. Bitcoin transforms energy into information that represents economic value. *Energy can flow from watts to bitcoins and back again*. We've never been able to do that. (Pilař, 2021, emphasis added)

Pilař is referring here to the first law of thermodynamics, i.e., the conservation of energy. However, he ignores the second law of thermodynamics, i.e., the law of entropy, ''which states that the energy disorder of any closed system tends to increase and points to a uniform equilibrium'' (Pasquinelli, 2010: 2). In other words, the energy spent on Bitcoin mining has been consumed and cannot be extracted from Bitcoin again. Pilař repeats the ''confusion suggesting that information processes negate the second law of thermodynamics'' (Pasquinelli, 2010: 3) – this conceptual shift demands that both of these measures be treated as abstract entities that are commensurable. However, ''informational negative entropy and thermodynamic negative entropy refer to two completely different scales of being and cannot be confused or considered homologous'' (Pasquinelli, 2010: 3). This commensurability is possible only as long as energy and information are treated as commodities. While the virtual battery depends on comparing volumes of energy without necessarily ascribing prices to these volumes, in this case, the process relies on evaluating both energy and information – objectified as Bitcoin – as independent commodities. Pilař further elaborates on the synergy of energy and information as a ''surprising resonance'':

> Do you notice the surprising resonance between the visions of a future energy grid based on clean, renewable sources and a global monetary network allowing energy to be stored as information? Their synergy will enable the liberation of energy stuck in time or space. (Pilař, 2021)

This resonance is surprising only if Bitcoin mining is considered to be the result of some autopoetic process; however, that is not the case (Tremčinský, 2021). The design of mining is neither apolitical nor technologically necessary, and it is informed by neoliberal theories of economic rationality (those of Hayek (1945)). The sacrifice of energy is therefore its ideologically informed part.

The commodification of energy and information in Bitcoin mining can also be found in an argument put forward by Karel Wolf, an economic journalist, who in the Czech edition of *Forbes Magazine* described the utilisation of surplus energy as follows:

> [Bitcoin miners] have the advantage of settling anywhere where electricity is cheap and can often afford the luxury of locating right next to renewable sources. They are also able to dynamically adjust their consumption according to the current state of the grid and external energy demand. The result is, in effect, a perfect energy arbitrage. (Wolf, 2023)

Here, the notion of arbitrage presupposes that both energy and information are circulating on various markets. As such, they have to be evaluated and can be valorised in exchange. However, my argument is that in Bitcoin mining, energy is not valorised in market exchange but through the sacrifice of energy in the mining process.

The enterprise of turning surplus energy into Bitcoin depends on two interconnected evaluations: energy is first evaluated as (almost) worthless or *waste*, and Bitcoin is evaluated as a priced commodity. As one article published in 2022 in *Bitcoin Magazine* put it: "Bitcoin converts wasted energy into a different kind of battery for

a more sustainable future. The battery of human time, effort, and ingenuity: money" (Koss, 2022). This evaluation of surplus energy as waste and Bitcoin as money/commodity is what allows Bitcoin mining to return a profit. Surplus energy, which is produced in a specific space and time of energy abundance and cannot be effectively transported to areas or time slots with a lack of energy, is utilised to mine bitcoins and is thereby transformed into a highly mobile and relatively liquid store of value. This logic is deployed by multiple miners around the world, including a Czech company, 2Bminer, whose computers are mainly connected in places with surplus energy, which would otherwise be wasted (Kinkor, 2024). Surplus energy that was initially evaluated as waste is then valorised as a digital commodity.

'Waste' is understood here in its comprehensive economic sense "as any material we have failed to use" (Gille, 2010: 1050). According to Asdal (2008: 129), such logic is underwritten by an economic rationality in which "not using resources effectively within economic reasoning equals a waste of resources". As Daggett (2019: 35) argues, industrial modernity was obsessed with managing the waste of energy in industrial machinery: "[i]mportantly, this was not the waste produced *by* the operation of engines, but rather the waste *of* the engines in converting coal into motion" (emphasis in original). This understanding of waste as the failure to metabolise specific energy sources effectively was connected to the Protestant work ethic (Daggett, 2019: 36). Bitcoin mining thus serves as an opportunity not to allow the energy to lie idle. Bitcoin's pseudonymous founder, Satoshi Nakamoto, therefore argued that "[t]he utility of the exchanges made possible by Bitcoin will far exceed the cost of electricity used. Therefore, *not* having Bitcoin would be the net waste" (Champagne, 2014: 236, emphasis in the original).

In summary, Bitcoin-as-battery rests on the evaluation of surplus energy as excessive waste. This evaluation then allows miners to use this energy and transform it into unique information. Despite some claims that the energy is stored in information, the second law of thermodynamics applies, which means that the energy is sacrificed in the process of mining due to entropy. The sacrificed energy adds to the security of the Bitcoin blockchain, supporting Bitcoin's evaluation as a durable digital asset. These modes of evaluation reproduce a historically specific capitalist logic of effectivity and wastefulness in which energy is put to work to produce commodities that are exchangeable on the market. The energy 'stored' in Bitcoin is consequently not valorised as energy but as some other commodity, a product of the consumed energy.

Grid-scale battery: valorising the stock

In recent years, Lithium-ion (Li-ion) batteries have become a source of political debate. Discussions in the international media and in academia frequently centre on the problems of mining 'critical minerals' used in Li-ion batteries, the fragility of global supply chains, the working conditions in the gigafactories producing batteries, and questions concerning the safe disposal and recycling of batteries (e.g. Bajolle et al., 2022; Ortiz, 2024). Li-ion batteries are used in consumer electronics such as smartphones, electric vehicles, and also grid-scale batteries, providing power storage to households, office buildings, and whole factories. In this section, I focus on grid-scale batteries, as they are considered a crucial component in the wider societal adoption of RES (White-Nockleby, 2022).

According to Czech news outlets, grid-scale batteries have begun to be more widely used in the Czech Republic over the past couple of years (Krýžová, 2024). In general, the Czech Republic has the highest ratio of battery capacity to installed RES capacity among household RES installations in the EU. However, it lags behind other European countries when it comes to batteries installed in industry (Krýžová, 2024).[8]

The first industrial grid-scale Li-ion battery was installed in the Fenix factory in northeast Bohemia in 2019 by its subsidiary, a start-up company called AERS (Advanced Energy Storage). After the installation was deemed successful, AERS started offering its battery solutions to other industrial clients.

By implementing the battery, Fenix was reacting to a specific problem in their manufacturing process. The company manufactures heating systems, which require working with sheets of metal at high temperatures. Therefore,

the process is very demanding in terms of the pace of labour. During relatively common electrical micro-outages (usually lasting less than one second), some of the company's computer-operated machines stopped working, and the whole production process shut down. Once it had stopped, workers had to wait until the metal sheets cooled down, then take them down from the production line, and start the process again. Such disruptions occurred up to thirty times a year, causing significant losses in the factory's output.

A grid-scale battery was introduced into the factory in 2019 to prevent these micro-outages from happening. The battery serves as protection against disturbances coming from the electrical grid. It improves the *quality* of the electric current by smoothing out its frequency. The electricity that comes from the grid is influenced by numerous factors, such as the grid load and the operations of the sources of the electricity, and the battery is able to absorb these irregularities and release energy with stable and more reliable properties (see Figure 1 below).

Using accounting practices (introduced above in the first part of the analysis of a virtual battery), energy can also be translated into a visual representation, enacting its dynamic character in time in the form of a graph. A graph is one of the crucial "metrological spaces elaborated by actors" (Vatin, 2013: 40) through which a battery is evaluated. In addition to presenting the frequency regulation, it is also used to demonstrate the other benefits of this device, such as *peak-shaving* and the *integration of renewables*.

Peak-shaving is a practice that especially helps big industries to reduce costs. Every large factory needs to acquire reserved power from the distributor. This amount represents the maximum power the consumer can take from the grid in a 15-minute interval. In industries that need a lot of energy to start their machines, such as electrical mills or ovens, these amounts are quite large. A factory can draw the additional power it needs during peak periods from a battery and thereby decrease the amount of power it takes from the grid during peak periods of demand. In the case of the Fenix company factory, the decrease in reserved power was approximately 25%.

These grid-scale batteries were first used as a device to improve the *quality* of the electric current and secure the smooth operation of the production line, and thereby minimise losses. The energy in the battery was therefore evaluated

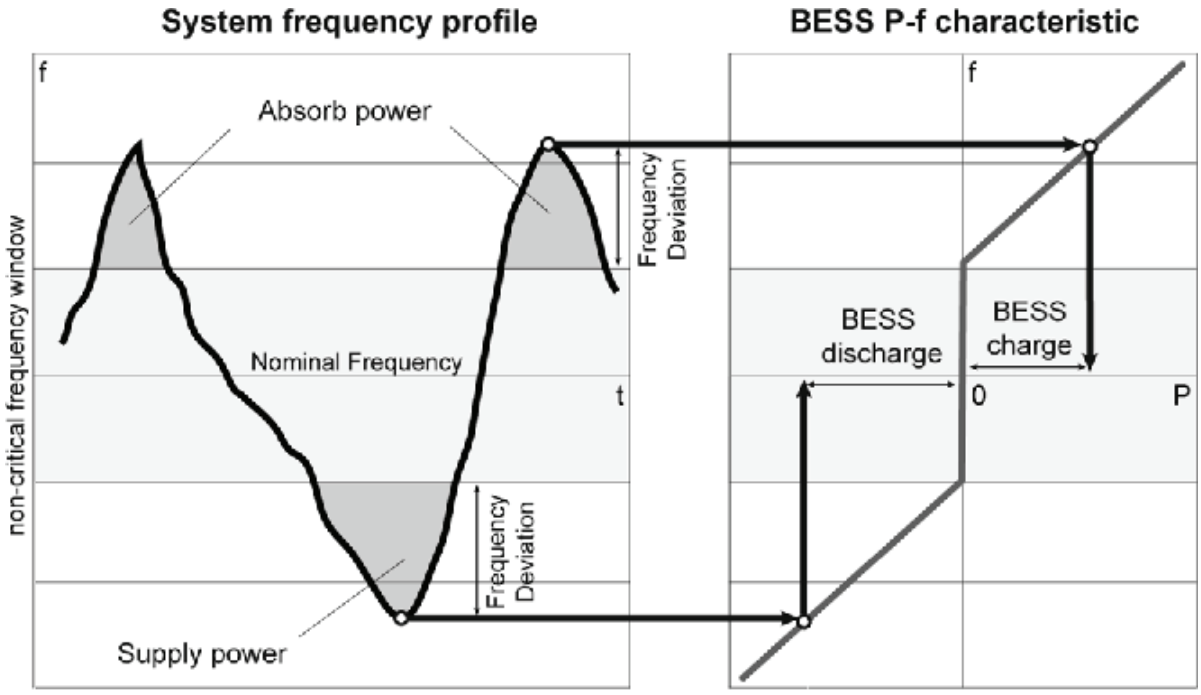

Figure 1. Absorption of energy when the frequency deviation is above the non-critical value and discharge of energy when the frequency decreases below the non-critical threshold. Approved reprint from Oudalov et al. (2007: 1262). Reprinted with permission.

against the average losses caused by micro-outages, i.e., waste. However, after a series of transitions, batteries were marketed as producing value and thus *valorising* energy. In 2021, Cyril Svozil Jr., the CEO of AERS, when asked about the other benefits of the battery system installed in the Fenix factory, mentioned (in addition to peak shaving and frequency regulation) only the possibility of storing surplus energy from the photovoltaics installed on the roof of the factory (Staněk, 2021). Two years later, in 2023, Svozil explained that these functions had become the least attractive:

> We called the industrial batteries SAS, a Peaking storage station [Špičkovací Akumulační Stanice], which was their primary purpose. However, today, since energy prices are what they are, this is actually perhaps its least required function. That is because it pays for the factory to have the reserved power contracted at a higher rate and then to be able to actively trade on the spot market – that is to say, to be able to charge the battery either from the sun through their photovoltaics or overnight when price levels are lower, and then to sell the energy to the grid when the prices are more attractive. (Zilvar, 2023)

Therefore, the new battery systems provided by AERS are now equipped with an automated trading algorithm that, according to Svozil, uses artificial intelligence and manages the trades on the spot market for the client (Zilvar, 2023).

This function can again be reproduced as a graph: the graph of the duck curve [in Czech ďáblovy rohy – or literally the 'devil's horns'] (Figure 2). A graph, as an evaluation device, is thus also used for the valorisation of the battery: "[i]n short, you have to *evaluate* in order to *valorise*" (Vatin, 2013: 35, emphasis in the original). This graph shows how the electric load from regulated sources (coal and gas) decreases significantly during the day because of the power produced

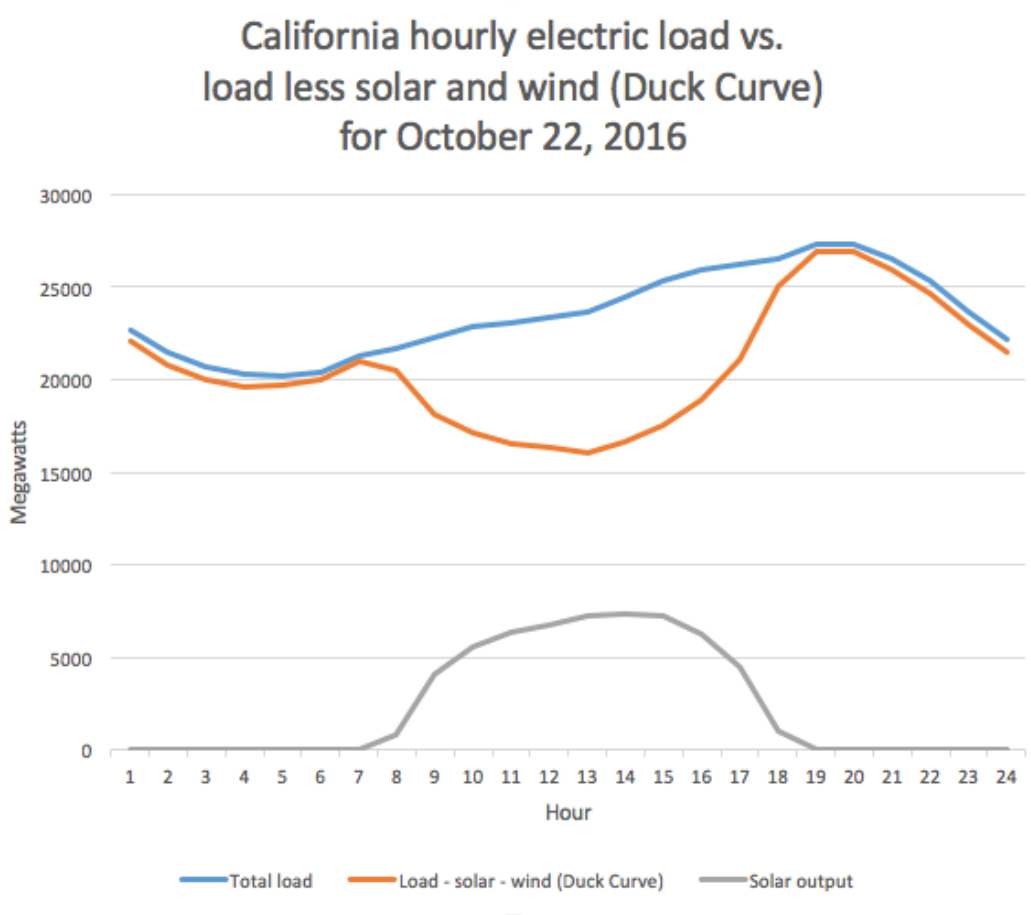

Figure 2. Duck curve in California, 22 October 2016. Arnold Reinhold / Wikimedia Commons, CC BY-SA 4.0. https://commons.wikimedia.org/wiki/File:Duck_Curve_CA-ISO_2016-10-22.agr.png

by photovoltaics. Therefore, the price of the electricity from RES is very small during the day and can even be negative (meaning that producers can even be paid to turn their plants off, and consumers can get paid for increased consumption).

The discrepancy between the supply and demand of electricity over time is not just an economic problem; it is also a technical one. Because the grid needs a balance of production and consumption for stable operation, there also exists a secondary market with system stability services that help to maintain this balance. So far, only a fraction of the batteries used in the Czech Republic can provide system stability services due to legislative constraints. However, the proponents of batteries (such as manufacturers and salespeople) argue that because of this legislation, the Czech energy grid operator (ČEPS) has to buy these services abroad. According to Jan Fousek, the CEO of the Association for Energy Storage (AKU-BAT), the amount paid by ČEPS for system stability services was approximately 800 million euros in 2022, and a significant amount of the capacity was obtained from Germany. For Fousek, this represents a clear, quantifiable illustration of the price that the Czech Republic had to pay for its outdated legislature (Fakta o klimatu, 2023).

The energy stored in a battery is thus valorised via speculation on the spot market and with the help of system stability services. When we consider the short history of grid-scale batteries in the Czech industry, we can see that they are going through similar frames of valuation as those described by Alexandra Bidet (2020: 127) in her study of French telephone service engineers: "The first valuation frame relied on an economy of forces, valuing the 'smallest loss': engineers mostly counted losses to reduce them [...]. The second frame values the production of utility: engineers invent an economy of the 'greatest gain'". At first, the battery was installed to reduce the costs of micro-outages and to decrease the reserved power. Later, its storage capacity became *valorised* via spot market and system stability services as a speculative asset. In modal terms, this trajectory exemplifies what Degani (2024: 74) describes as a *key shift*: an environmental input – here the surge in electricity prices after 2021 – does not merely elicit a response but reorganises the mode in which subsequent inputs are responded to. The same physical device was thrust across a threshold, from a medium of loss-prevention into a medium of speculation, and with it shifted what its owner may and must do with the energy it stores.

Electricity is characterised by flow. Batteries make it storable, and in doing so lend it a basic property of stock — one previously available only to fuels. Simpson (2019: 111) argues (initially referring to oil) that stocking serves "as a type of spatial fix for the [fuel], allowing excess [fuel] to be temporarily taken out of circulation at moments when there is a glut of cheap [energy] flooding the market and driving prices down". It is very symbolic that many grid-scale batteries are placed in shipping containers, which are themselves a material symbol of stockable commodities. Thanks to this device, energy becomes more mobile and, most importantly, storable, which allows energy arbitrage. The possibilities of evaluation and valorisation can be communicated through various graphs that demonstrate the intermittent character of electricity that comes from RES. The goal of the grid-scale battery is to absorb this intermittence and thus make the electricity more manageable. This process of absorption is also a process of abstraction. Electricity from RES has specific properties that determine its quality and its distribution in time and space. Through the information metric and the energy arbitrage, the processes of electricity production and consumption become synchronised. Batteries make it possible to abstract electricity from its source and thus make it marketable.

Across the cases studied here, batteries consistently function as valuation devices that translate intermittent flows into forms that are legible to markets. What varies is not whether they 'black box' valuation, but the modality through which they do so: as accounts (virtual battery), as waste sacrifice (Bitcoin), or as speculative stock (grid-scale storage). Seen together, these modalities reveal different strategies for rendering renewable energy commensurable with capitalist value logics.

Modalities of energy in transition

The modalities that are activated in different valuation moments are not exclusive to the specific battery (see Table 1 below).

Looking at the virtual battery, we see that energy is standardised and accounted for in the form of credits and debits. Because this energy cannot be consumed by the prosumer directly at the moment of production, it is evaluated as excess or waste. Ideally, the valorisation of this energy would occur through its later consumption during the winter season, when there is little to no electricity generated from sunlight. However, because of flat-rate fees and the design of the product, this valorisation is often negative, meaning that prosumers end up paying more than they would with alternative arrangements. In practice, it is the distributor who truly valorises the energy, profiting by collecting the flat-rate fees while also gaining from the sale of the surplus electricity.

An accounting operation must also be carried out in the case of Bitcoin, where the costs of running a mining operation are compared with the potential yield. The energy required to power mining hardware has to be measured and accounted for, and only when sufficient energy can be evaluated as waste or excess does the operation have the potential to be profitable. The valorisation of this surplus energy is mediated through information that is transformed into unique digital objects: bitcoins. Since the price of bitcoins is highly volatile and dependent on the market behaviour of other investors (Tremčinský, 2021), this valorisation remains speculative. Bitcoin miners gamble that the combined costs of energy, hardware, and personnel will be lower than the Bitcoin rewards they receive for their computational labour.

Last but not least, the grid-scale battery also accounts for the energy it stores. This accounting does not just concern the number of kilowatt hours that can be accumulated, but also the peak power the battery can deliver to supplement the factory's reserved power. The stored energy is again evaluated as excess, whether originating directly from the operator's renewable production or from a market surplus signalled by low spot prices. It is important to stress that energy sold on the spot market is likewise evaluated as surplus or waste: within the logic of the price mechanism (Hayek, 1945), energy that cannot be consumed at the moment of production is devalued and therefore sold at a discount. The same market also enables valorisation, when this energy is later sold back to the grid. The practice of buying low-priced surplus energy and reselling it at higher prices thus constitutes a form of arbitrage. As with Bitcoin, this valorisation is speculative in nature, though here it is not mediated by digital objects but by the direct circulation of electricity.

Reading the three cases side by side also raises what Degani (2024: 69) calls *meta-modal* questions: for any given agent, which modalities are accessible, and how probable or reversible is shifting across them? The batteries examined

Table 1. Moments of valuation and modalities of energy in three different types of batteries.

Type of battery	Moments of valuation		
	Accounting	***Evaluation***	***Valorisation***
Virtual battery	**Account** [energy debits and credits]	Waste [energy that cannot be directly consumed at the time of production]	Consumption in winter [negative valorisation resulting from flat rate fees]
Bitcoin-as-battery	Account [excess energy available for mining]	**Waste** [energy that has no other profitable use in a particular time and space]	Bitcoin as a commodity [mediated speculation]
Grid-scale battery	Account [excess energy either produced or obtained on the market]	Waste [available energy that overflows the consumption curve and is available for arbitrage]	**Stock** [direct speculation with energy as a commodity]

here distribute this modal mobility unevenly. The distributor behind the virtual battery moves freely between the account and the market, trading the surplus it acquires at no cost, while the prosumer remains confined to the account and its asymmetrical clearing rules. Bitcoin miners are mobile by design, able to relocate wherever energy can be evaluated as waste, whereas the grids whose surplus they absorb are not. The factory, equipped with a grid-scale battery and a trading algorithm, can alternate between consuming, storing, and selling as prices dictate; the consumer without one must take the price as given. For some actors a modality of energy is thus worn lightly and switched at will; for others it hardens into a constraint. The asymmetries of the energy transition are in this sense not only asymmetries of appropriation but also asymmetries of modal mobility: of who may switch between modalities of energy, at what cost, and who must remain within the mode assigned to them.

Conclusion

The distinct physical properties of RES require new knowledge practices if energy is to remain commodifiable. The technological solutions discussed in this paper are designed to maintain the capitalist order by reproducing electricity as an accountable, cheap, and storable form of energy that can be appropriated and valorised in the process of marketisation and consumption. Hence batteries join "the globalised ensemble of technological artefacts" which serve as "the physical scaffolding (the morphology, so to speak) of world society", while the flows of information, money and resources "are its physiology" (Hornborg, 2021: 214).

In this paper, I presented three modalities of energy – account, waste, and stock – that have been brought forward by the new information-processing assemblages, namely, batteries. These modalities are not new, nor unique to batteries, but thinking of batteries as information devices allowed me to explore how these modalities are enacted within the broader assemblage of the energy system and how, when put together, they enable the continuous commodification of electricity from RES. Those modalities are not exclusive to each type of battery; each case serves as an exemplar through which these modalities are made visible. While the cases differ in their technical details, they all enact the same underlying logic: excess renewable energy is accounted, evaluated, and valorised so that it can be commodified. In one case this takes the form of credits and debits (virtual battery), in another it is represented by the transformation of excess waste energy into a digital commodity (Bitcoin), and in the third case this logic is illustrated through the stabilisation of energy as a storable stock (grid-scale battery). Each modality shows how valuation practices absorb intermittency into marketable forms via knowledge practices of producing information to control the flows of energy.

Understanding batteries as media of modality, finally, situates the energy transition within what Degani (2024) identifies as an era of planetary counterfactuals. The transition to renewables is a shift in the medium of collective life, and like any modal shift it unlocks certain possibilities while locking up others. The modalities documented here – account, waste, and stock – show the possibility space of renewable energy being configured such that the actions that remain possible, and those that become necessary, are those of capitalist valuation. Yet the modal proposition that other worlds are possible cuts both ways: the same intermittent flows could, under different accounting conventions, market designs, and infrastructures, be enacted in modalities other than those of the commodity. Describing what energy in transition may and must be is therefore also a way of asking what else it could become.

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Notes

1 Andreas Malm (2013), in his analysis of the emergence of fossil capitalism, argues that capitalists' choice of fossil fuels as the preferred source of energy was not due to the fuels' higher efficiency or lower price but to their mobility and to the more accessible employment of urbanised labour power.

2 The term 'intelligence' here is understood in the sense of reconnaissance and command rather than cognition (e.g. military intelligence, secret intelligence, etc.).

3 Valorisation is used throughout in Vatin's (2013) sense of augmenting the value of a good. The term resonates with, but is not identical to, the Marxist concept of valorisation (*Verwertung*) as the self-expansion of capital through the extraction of surplus value; where the Marxist register is intended, as in the discussion of Bryer's theory of accounting, this is indicated explicitly.

4 In the Czech Republic, the distribution fee is regulated by law.

5 See the discussion at the Solar forum: https://solarforum.cz/viewtopic.php?t=230.

6 https://ccaf.io/cbnsi/cbeci. For comparison, the annual electricity consumption of the Czech Republic in 2021 was 63 TWh, or of Poland 160 TWh.

7 Modern money is, in theory, opposed to so-called special or primitive money that fulfils only one or two of the aforementioned functions (see Dalton, 1965; Maurer, 2006; Zelizer, 1989).

8 Proponents of energy accumulation mainly blame inappropriate legislation, which does not allow subsidies to be drawn, requires lengthy permission processes, and does not allow batteries to be connected to the system stability services that help to stabilise the electricity grid.

Radical Planetary Propositions and their Ethical Limits

James Maguire

IT University Copenhagen, jmag@itu.dk

Abstract

This paper examines a radical proposition for planetary futures: a collaboration between a group of synthetic biologists and a design collective interested in exploring the role of DNA as a digital storage and climate technology. Central to this collaboration is the use of speculation, both as an explicit design method and as an implicit technique used by synthetic biologists to imagine indeterminate future states. The paper highlights how biologists imagine such future states through contemporary limits and gaps in their understanding, and how such a practice inflects ethics as a particular kind of concern. Such an inflection, the paper suggests, cannot be considered an absence of ethics, but rather an ethics of absence: a means of doing ethical practice that puts doubt into abeyance. This, the paper argues, is a considerable problem for the role of speculation in imagining more radical planetary futures. Radical planetary propositions, need, the article suggests, far more radical ways of imagining future ethics.

Keywords: Ethics, Speculation, Planetary Futures, DNA, Data

Introduction

This paper arose from a collegial provocation to think through the planetary foundations of environmental knowledge production, particularly as mediated through digital infrastructures. Such a framing is premised upon the idea that western epistemologies tend not to take sufficient account of the conditions of their own production, be it the planetary artefacts that constitute objects of knowledge or the digital infrastructures that mediate them. Such a framing implies a lacuna: the idea that our knowledge infrastructures background, make invisible, or underdetermine the mediation work of both planetary materials and digital infrastructures (themselves constituted through such materials). Science and Technology Studies (STS) and cognate disciplines have invested considerable effort trying to address this gap, providing detailed ethnographic and conceptual accounts of the materialities, quantifications, and forms of politics that compose these mediations.

What these studies make visible is the oftentimes recursive relations between planetary conditions, knowledge production, and digital technologies: what this article frames as the *planetary-digital-knowledge nexus*. They are so intertwined that their multiple overlaps, loops, interdependencies, and complicities have become a serious barrier to planetary change as both a conceptual and political project. For those working to alter the course of things to come

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– not least the catastrophic climatic trajectory we are facing – untangling these interdependencies and complicities to put forth a plausible conceptual or political project is, to say the least, daunting. And so, while there is no shortage of critique of our current planetary predicament – its histories, legacies, and futures – the role and nature of such critique in these urgent times is somewhat less clear (Anker & Felski, 2017). In particular, the position from where such critique is generated oftentimes obscures one or other part of the aforementioned nexus, leaving particular gaps or highlighting particular limits that make such political projects less tenable. In this sense, imagining worlds beyond this nexus is one pathway to formulating more radical visions for planetary futures.

This article engages with one such vision: a collaboration between synthetic biologists and a speculative design group interested in DNA as a digital storage technology. This mutual interest led to the development of an installation, *The Data Garden*, showcasing an organism-based art-science prototype that confronts, critiques, and speculates on the role of biotechnologies in more habitable planetary futures. The installation poses a simple yet provocative question: what if data could be stored in plants? From this question emerges a series of design interventions around, amongst other things, how we might re-imagine the role of digital infrastructures in the climate emergency: from scorching the earth (Crary, 2022) to its potential regeneration. At the same time, such a question provokes thinking around the immense challenges and potential flourishing of emergent forms of collectivity (plant-data-human hybrids). And as this project involves interacting with living systems through the transformation of genetic information, its ethics are, thus, central. In essence, the installation is an effort to bring a more-than-human sensitivity to bear in re-imagining how digital infrastructures mediate planetary-knowledge relations. This paper, thus, reframes how we might think about the environment, its potential collectivities, and their concomitant ethics.

Central to the studied collective is the use of speculation, not just as a design methodology and tool of critique, but as a more radical means of reimagining the planetary-digital-knowledge nexus entirely. This article pays attention to the implications of such speculation, with a particular focus on how its ethics are enacted in practice. The paper goes on to argue that what emerges is an ethics of absence: not an absence of ethics, but a means of practicing ethics that diminishes the ethical force of the collective's radical proposition. This, the paper argues, is a considerable problem for the role of speculation in imagining more radical planetary futures.

The article proceeds through multiple steps. First, it introduces the collective, contextualising and situating their work, approach, and practices. Second, it engages with emerging conversations around what I call the *planetary-digital-knowledge nexus*. The purpose of this is to highlight the recursive complicities and interdependencies that such a nexus produces as well as how they might pose a problem for developing more radical propositions for planetary futures. After discussing the paper's methods, I go on to describe the contours of the collective's installation – *The Data Garden* – as a form of speculation that entirely reimagines the *planetary-digital-knowledge nexus*. And finally, I reflect on the preceding lines of enquiry by discussing the knowledge gaps and their concomitant ethics that these speculations afford.

Radical planetary propositions

Grow Your Own Cloud (GYOC) – cofounded by Cyrus Clarke and Monika Seyfried – started its life as a relatively limited design critique of climate futures, examining the various ways the data-industrial complex impacts the environment. However, over time, it matured into an extended critique of planetary digital infrastructures. This critique encompasses the datafication and surveillance tendencies of late capitalism, the mystifying rhetorical devices of the platform economy (think the 'cloud' metaphor), and the planetary environmental costs of digital infrastructures. For example, the resource needs of the data industry are well known. Its sprawling planetary infrastructures create vast quantities of waste and toxicity, typically in countries and places that continue to act as global capitalism's 'cheap' extraction sites. Whether it's the rare earth minerals and metals

that supply the materials to build our digital infrastructures, the energy and water needed to process them, the cheap labour needed to assemble them, or the waste accumulation in our disposal of them, the environment is very much under siege.

But GYOC has become disenchanted with 'merely critical' approaches to design interventions. Mobilising critique as a diagnostic tool to destabilise contemporary understandings of the relationship between the 'internet complex' (Crary, 2022) and the environment, was, according to the founders, simply 'not enough'. Teaming up with scientists is what enabled them to work at the frontiers of research focusing on ethics and technology, and more particularly, genetics and synthetic biology (more on this below). These encounters pushed GYOC to reexamine their own assumptions and presuppositions. In lieu of a diagnostic model, they moved towards a reparative one oriented around speculation. In speculation, GYOC found the freedom to balance their impulse toward critical engagement with their instincts to imagine more re-generative scenarios. GYOC thus grew out of a desire to imagine a new model for digital data management *outside* the realms of the current information capital and technocentric models. But reimagining secure, regenerative, decentralised data management techniques that counteract the destructive anthropogenic activity of data storage itself required a more radical approach.

Such radicalness arrived in the unusual form of a group of synthetic biologists working at the Molecular Information Systems Lab (MISL) at the University of Washington. The lab traffics at the intersection of computational and biological systems, exploring the connectivity between information technology and molecular biology. This includes research on molecular data storage, synthetic biology, molecular sensing, and cyber-biosecurity (Molecular Information Systems Lab, 2025). Traditionally, the computational sciences have played a supporting role in biological enquiry, providing novel computational methods to help solve biological problems. One of MISL's broader mandates has been to invert this arrangement by mobilising biological resources and theories in the service of computational problems. In particular, they are interested in pushing at the frontiers of data storage, prototyping new storage mediums that are not subject to the whims of technological obsolescence. For researchers at MISL – alongside other researchers at this self-proclaimed frontier – biology becomes the model for thinking about and designing future data storage technologies. In fact, biological entities are envisioned as storage technologies par excellence, leveraging evolution's sophisticated means of storing 'data' over vast temporal horizons. But for Jeff Nivala, co-director of MISL, such storage technologies are but one step on the road to a far bolder speculative vision. Nivala outlines a world where nano-bio sensors comb through various environments (perhaps the gut or one's blood stream), recording sensory data as they go. Here 'sentinel cells' – with embedded molecular recording devices – record their surroundings and implant the molecular data within the cell's genome (to be retrieved at a later date and translated into a readable format). Nivala imagines these devices, in time, becoming economic and scalable, 'democratising' as he puts it, genomic research, as it opens itself up to broader publics. The retrieval of such bio-sensory data is imagined to open a cornucopia of possible applications within medicine, human health, and the environmental sciences.

Such optimism, however, has a history to it. As STS scholar Jenny Reardon (2019: 178) points out in *The Post Genomic Condition,* genomic research is infused with "grand visions of purpose – from revealing the secrets of life, to countering racism, to democratising science". In fact, in attempting to shed its problematic racial legacies, the discipline's transition from genetics to genomics marks a liberal turn towards issues of transparency, inclusion, and democracy. While such hopeful discourse has produced vast investments in genetic research, it has not, according to Reardon, resulted in the medical breakthroughs that the industry has promised. The majority of these investments have been funneled into sequencing technologies, enabling researchers to transform DNA into data at an unimaginable scale. On the one hand, the production of such vast troves of data has been framed as improving access for more marginalised groups, as well as contributing to more democratic, less racist, and on the

whole, more just genetic practices (Reardon, 2019: 8). On the other, the sector's incapacity to make meaningful assessments of value about what all these data are 'good for' (a question to which we will return in the last section) continues to plague genomics. These histories inform the work at MISL as it continues to tap into the investments arising from bio-informational capitalism, adapting sequencing technologies to inform its research on data storage. But such legacies are not only about capital investments, this sense of genomic liberalism that Reardon describes is still very apparent in MISL's desire to 'democratise' new technologies and open their work up to new publics. In a sense, then, the world of genomics is strongly characterised through data (its meanings, uses, and values) (Tallbear 2013a, Fortun 2023), and as we shall see, the problem of data storage as rendered by MISL centers data as a means of altering the course of things to come, albeit in a radically different way.

The computational-biological interface provided the meeting space for GYOC and MISL (henceforth referred to as 'the collaboration' or 'collective'). As designers with a history of engagement in computational technologies (GYOC) and synthetic biologists working at the frontiers of bio-technological possibility (MISL), their collaboration grew out of a mutual curiosity about the role of biotechnology in planetary futures. While it is MISL's scientific state of the art that informs the design and creative process of the collaboration, it is GYOC's art and design techniques that pushes the boundaries of what science and technology might deliver.

An important backdrop to the collaboration was a groundbreaking paper by MISL researchers published in 2017 in the high-profile journal *Nature*. Here the team wrote up the results of an experiment that was the first to encode a moving image (GIF) into the genome of a population of living e-coli bacteria (Shipman et al., 2017). This process involves two distinct components: the *writing* of digital bits into DNA (what one could think of as the upload phase) and the *reading* of this DNA back into digital formats (the download phase). MISL researchers used a bespoke system to *write* a few hundred kilobyte GIF into DNA code: essentially translating 1's and 0's into DNA nucleotides A, T, C, and G. While a large DNA synthesis company – Integrated DNA Technologies – synthesised and encoded the actual DNA strands, the team inserted these strands into a living organism by engineering E. coli with CRISPR enzymes CAS1 and CAS2. Such CRISPR proteins 'grab' free-floating pieces of DNA within a cell and integrate them into the genome at a precise location. Once this is done, the cells can be cultured so that the encoded DNA replicates just like any other part of the genome (Shipman et al., 2017; Meiser et al., 2022). As MISL researcher Jeff Nivala remarked to me: "for all intents and purposes, this DNA is simply part of the genome." *Reading* the DNA back into digital data requires taking a sample of this bacterial culture and inserting it into a PCR (polymerase chain reaction) machine. This technique allows researchers to identify segments of DNA within the genome where their data is stored (CRISPR enzymes allow for this possibility), which they subsequently amplify and copy. The copies containing the encoded DNA strands are then inserted into a nanopore DNA sequencing machine to read out that specific sequence in DNA code. This DNA code is then input back into the bespoke decoder program on a computer which decodes and converts that DNA sequence back into the digital bits that had originally been encoded. After seven days of growing the bacteria, or forty generations, the experiment was ended.

Biotechnology and art are intertwined in complex ways (Rogers, 2021; 232) and the boundaries between them are oftentimes more porous than standard accounts recognise. And while this will not be news to STS scholars interrogating the art-science complex (Slater 2021), what is striking in this case is how collaborating with speculative designers has opened pathways that 'regulatory science' (Vera, 2023: 67) has, in some sense, closed off. In recounting the role of DNA as a practical digital storage technology, MISL co-director Jeff Nivala is clear in his assessment: the obstacle to storing digital data in living cells is more economic than scientific. At current scales and costs the only reasonable 'value-proposition' for DNA storage technologies is to store archival data. In these settings the process stops at writing digital data to DNA. That is, the encoded data is translated into synthetic DNA to be stored in vials until some unspecified time in the future. The economic

incentive here is to store cultural heritage (and other) items in such vials enabling them to exist in a stable and retrievable form long into the future. In this sense, it is the potential of DNAs density and durability that facilitates a workable market proposition. And although this causes its own set of translation issues down the line, it is, quite literally, a worry for *another time*. The collaboration with GYOC, from Nivala's perspective, is thus one that frees them from the economic logics embedded in their practices and unleashes the speculative potential inherent in their process. In this sense, then, the mediating power of the market and its concomitant techno-political forms – the usual obligatory passage points through which planetary problem spaces and their potential solutions are formulated – inhibit various, and otherwise more radical, planetary propositions from surfacing. Speculating with GYOC via an installation known as the *Data Garden* became one means of undoing the boundaries imposed on these more radical planetary propositions emboldening the collaborators to reach new publics through new media.

Methods and positionality

As a researcher operating at a not dissimilar interface and with a particular interest in the politics of energy and data storage, my path crossed GYOCs through a reference from a colleague. Frustrated by the fortified walls of the data center industry, I was curious about alternate method assemblages that might open research pathways beyond the highly curated environments that one confronts in the data center sector. Encounters with data center actors are notoriously difficult: access is restricted, physical locations highly securitised, conversations are mediated by non-disclosure agreements, and spaces of engagement are oftentimes limited to the overly choreographed settings of conferences or tailor-made workshops. Above all else, protecting a tightly woven techno-optimistic narrative is foremost on industry's mind. Fascinated by alternate imaginings of data storage and management, I reached out to GYOC. From this, we organised a series of online conversations with the aim of developing a collaborative paper for a special issue (Maguire et al., 2024b). This work snowballed into a series of interviews with synthetic biologists at MISL and elsewhere, leading me into an analysis of their scientific papers, media outputs (videos, podcasts, interviews) and websites (all MISL related content in the prior section is based on these materials). It was through these engagements that my interest in speculative methods developed and became the cornerstone of this paper, the purpose of which is to understand the relationship between speculative methods and ethics. More specifically, I ask: what forms of ethics inhabit speculative approaches to planetary futures?

Before describing the installation that GYOC and MISL developed, I want to spend a little bit of time engaging with emerging conversations around what I call the *planetary-digital-knowledge nexus*. The purpose is to highlight the recursive complicities and interdependencies that such a nexus produces and, in doing so, set the stage for speculative practices that try to, in some sense, escape such interdependencies. In essence, the collective's argument is that developing more radical alternatives for planetary futures requires moving *beyond* the constraints of techno-industrial capitalism. But what the paper will go on to explore is the ethical inferences that such a move entails. As I mentioned earlier, at the heart of contemporary genomics is a surfeit of data: such rich data worlds are the seed of all potential future medical discoveries. At the same time, the sector has become bogged down in ethical questions of how to meaningfully interpret and use all this data towards some 'moral good' (Reardon, 2019). As we will learn, this question is also at the heart of the collective's speculative practices.

The planetary-digital-knowledge nexus

It is difficult to think about contemporary environmental issues without considering their digital co-constitution. Much of the time, environmental knowledge making is digitally mediated and these mediations are oftentimes composed of environmentally sensitive materials (rare earth metals, for example). Epistemic questions on how we come to 'know nature' have been central in the production of environmental knowledge for some time now. Some years ago, anthropologist and STS scholar Kim Fortun explored the important role

of data within environmental politics, suggesting that "environmental information systems *structure what people see* in the environment, and how they collaborate to deal with environmental problems" (Fortun, 2004: 54, emphasis added). The work of Paul Edwards (2010) and Geoffrey Bowker (2008) has also spoken to the role of the digital in the making of environmental knowledge, in particular pinpointing the infrastructural mediations that are central to this (Maguire et al., 2024a: vi). Today, the environment is being remodeled through various AI driven techniques (including machine learning algorithms) that have begun to see and know the environment anew. Work on species monitoring (Turnbull et al., 2023) and climate adaptation and mitigation (Rolnick et al., 2019) are some of the most prevalent. Here we see the deployment of epistemological modes that valorise precision, optimisation, and abstraction (Machen & Nost, 2021). In doing so, they claim to make ecosystems more intelligible, knowable, and actionable. But recent critical work has also demonstrated that it matters who does the sensing and knowing and in what ways they are done (Gabrys, 2014, 2020).

But digital technologies themselves depend upon the long history of the planet. Developing technologies that shape environmental data production implies extracting rare earth metals at vast scales: coltan, lithium, nickel, for example. And their extractive, and oftentimes, violent politics have been well documented (Mantz, 2008; Ureta & Flores, 2022), including what goes under the banner of 'green extractavism' (Acuña & Tironi, 2022; Blair et al., 2023; Riofrancos, 2025).

Here we see a recursive relationship: as rare earth metals produce the digital, those very same data producing digital technologies contribute to how we understand rare earth worlds, their toxic effects, as well as the range of injustices they contribute to. From this we gain purchase on the colonial logics that underpin such extractive regimes as well as the similarities between these material extractions and the data extractions they facilitate (Kidd, 2019: 956). So, as data worlds are materially constituted through the extractive logics of their metals and minerals components, these worlds also reproduce those very same logics by facilitating the rampant extraction of citizen data. Here, colonial pasts and presents conjoin in the logic of extraction. But the planetary emergency interrupts computational processes showcasing how vulnerable digital worlds have become (Maguire et al., 2024a: ix). Here, we see another recursive loop: as planetary destabilisations threaten digital worlds, those digital worlds inflame the very same problem through their own resource exploitation. These complicities highlight that digital infrastructures are reliant on material foundations, the cables, routers, and energy sites - to name but a few – upon which computational architectures depend. Work from within what's known as 'Climate AI' puts particular emphasis on AI model training and inference work, arguing that training models can emit the equivalent of five times the lifetime emissions of an average American family car (Strubell et al.; 2019; Kaack et al., 2022). What this points out are the various forms of dependency that planetary connectivity relies upon: routing technologies, internet protocols and standards, electricity grids, cooling systems, labor, economic devices and models, and importantly, various values and imaginaries (Johnson & Hogan, 2017; Maguire and Winthereik, 2021; Maguire et al., 2024a: ix).

But it is difficult for researchers to access data on the local effects of the planetary crisis on digital infrastructure. Getting past security fences, access barriers, or the plethora of non-disclosure agreements that litter the municipal offices where agreements and contracts are brokered is a challenge (Maguire & Winthereik, 2021). Despite this, digital technologies continue to be sought out at ever increasing scales as a means of accumulating more evidence (data) on the state of the climate emergency (Maguire et al., 2024a: ix). Data has become central in 'organising the problem' of environmental destabilisation and as such we see the rise of data advocacy in various parts of the world, coalescing around shared ideas of data justice and equality (Dencik et al., 2019: 875).

What I hope has emerged from this exposition of the planetary-digital-knowledge nexus is their recursive relations: their overlaps, loops, interdependencies, and complicities. Digital infrastructures play an important role in mediating environmental knowledge, that much is clear. But they are also objects that are environmentally infused, and this infusion is, at the same time, an environmental problem. Yet these technologies are enrolled as tools that describe and quantify

those very problems. In some sense, then, they perform a double mediation: they mediate environmental knowledge while simultaneously mediating the deleterious effects of producing this knowledge – its toxicities, wastes, and pollutants. Similarly, in producing knowledge on current planetary instabilities, digital infrastructures are also subject to them. As such, they too are under duress. And here again, we see how they are complicit in the conditions of their own instability, whilst concomitantly being tools that calculate and quantify the risks associated with these endeavors. What I want to emphasise is that such recursivity is a serious problem (both conceptual and political) for those pushing for planetary change. In particular, the ground from which such actors' critiques are generated oftentimes obscures one or other part of the aforementioned nexus, leaving particular gaps or highlighting particular limits that make such political projects less tenable. Take the degrowth movement as one example of more radical planetary propositions: Even here, there is oftentimes a myopia towards the role of technology in generating such futures: digital worlds are conceptualised less as 'the internet-industrial complex' a 24/7 consumer-administrative-surveillance panopticon and more as 'tools' that can be appropriated for the 'good' of the planet.

As critical and post critical thinking suggests, critique from *within* is hampered by the broad scale institutionalisation of critical processes (Anker & Felski, 2017). In its reduction to but one more pedagogical tool or research method, critique – and its power to achieve social and political transformation – has lost much of its militancy and urgency (Hardt, 2011; Malm, 2023). For example, one can see how the pervasive power of capital has appropriated the forms of critique the climate emergency has generated. Both climate governance and policy circles are engulfed with the language and praxis of green transitions, decoupling, or other green-capital intensifications, the now dominant pathways for building more climate friendly futures. Such pathways, as is evidently clear, are unlikely to be sufficient. In this sense, such critique has, indeed, run out of steam (Latour, 2004). For the collaborators of this project, then, speculating about worlds beyond the planetary-digital-knowledge nexus is one pathway to formulating more radical propositions for planetary futures. In the sections to follow, I will outlay this project and its ethical implications.

Reimagining the planetary-digital-knowledge nexus

While the research paper in Nature formed the scientific backbone for the collaboration between GYOC and MISL, it was GYOC's planetary futures concept that framed it. Designing a simple, yet provocative, question – what if data could be stored in plants? – became the means of speculating with DNA as an alternate data storage technology that inverts the carbon and mineral intensive pathways of contemporary data infrastructures. As mentioned earlier, GYOC have long critiqued the planetary warming and extractivist propensities of such data infrastructures and their collaborative proposition with MISL was to imagine an ecological-technological ('eco-tech') relationship beyond the extractivist paradigm that positively contributes to planetary cooling.

In 2018, GYOC developed a more delimited project (a precursor to their collaboration with MISL) in association with the University of Copenhagen's Plant Genetics Lab, known as the *Data Flower Shop*. Here participants (shop customers) were asked to upload pieces of data to a website. Choices ranged from self-composed poetry to pictures of recently deceased pets. They were then invited to a simulated data-to-flower upload experience at a flower shop in Copenhagen. The GYOC team walked participants through a range of steps, guiding them in, for example, how to choose an 'upload flower,' thinking about its aesthetic qualities alongside its functionality. Should it, for example, pollinate? Should it have a long or short lifespan? They also explored questions around the duration of storage. A bouquet, for example, was imagined to store data for a short period of time. Or a small bonsai tree for a longer duration. The purpose for the organisers was to gather initial responses to the general idea of storing data in living organisms. From the scientific perspective, this was an entirely fictional process: a simulation of uploading a memorable piece of data

into a living organism. What it did point towards however – and perhaps unsurprisingly – was the various ethical issues that the simulation gave rise to, particularly how such techniques might 'harm' the environments they were, in essence, programming. This first attempt, then, facilitated discussions around evocative topics such as data and biotechnology, planetary futures, and ethics. And while it lacked scientific framing, expertise, and resources, it did generate a set of understandings and concerns that led to the development of the collaborative *Data Garden* installation.

The *Data Garden* installation was presented at various locations between 2020 and 2022, including South by Southwest (SXSW), a large festival held annually in Austin, Texas. In Europe, a modified version of the installation was presented (Ars Electronica in 2021 and Bozar, Brussels in 2022) due to restrictions on the use or exhibiting of genetically modified plants. The collective describes the Data Garden as an "organism-based science-art prototype that explores and challenges current data infrastructure hegemonies" (Grow Your Own Cloud, 2025). In essence, a speculative prototype of a carbon negative data infrastructure which uses synthesised DNA stands to store digital data within, and retrieve them from, living organisms. The concept for the installation was to evoke a speculative data infrastructure using cutting edge synthetic biology techniques to probe, critique, and intervene in current modes of organising data's relationship to the environment. It challenged visitors to think outside the frame of large, centralised, energy and materials hungry data servers located in problematic ownership structures, calling their attention instead to a set of alternate arrangements that speculated with DNA storage technologies as collectivised (and localised) carbon negative sites. To do so, the core installation (see Figures 1 and 2 below) was supplemented by a range of materials, including texts, images, interactive spaces, and a manual.

As a science led design project, the installation drew upon forms of *futuring work* that have a long history within design thinking (Bleeker, 2009; Dunne & Raby, 2013; Jenkins et al., 2020, Rosner, 2018) as well as STS (Downey & Zuiderant-Jerak, 2021; Haraway, 2016; Jungnickel, 2022; Wilkie et al., 2017). It was inspired by scholars interested

Figure 1. Data Garden installation (Photo by Monika Seyfried)

Figure 2. Decoding process in the Data Garden Installation (Photo by Monika Seyfried)

in both *speculation* and *intervention* as a means of doing knowledge work: the use of design objects to provoke thinking about the future by facilitating spaces where people can speculate about, and hence re-imagine, the world. Whilst the methods for achieving this are quite variable (classic design, co-production, ethnography), what they share is a commitment to speculation as a device for imaginative intervention in the course of things to come. In this sense, then, the installation is an invitation to visitors to explore an emerging science through an artistic prototype: a rehearsal, of sorts, of a 'not quite yet' future (Corsin Jimenez, 2017: 3; Maguire, 2018) that regulatory science cannot facilitate. From the collective's perspective, affording visitors an experience of alternate ecological-technological materialities and relations is one way to provoke ethical reflections on the role and potential of biotechnology in planetary futures. It prompts an enquiry into, and a critique of, science and art, while reimagining a new planetary-digital-knowledge nexus.

Within the installation, the plants are housed in one long post-industrial pipe that arcs in the form of a bow of almost 180 degrees, supported by a larger green scaffold that frames the entire space. The installation is radiated in alternating pulses of luminescent purple light sequences. Haunting post-apocalyptic music amplifies the already resonant eco-tech aesthetic as data and numbers pulsate across a large white circular graphics interface that is mounted in the middle of the installation. In front of this frame is a table, upon which sit various scientific objects (vials, decoders). The narrative voice-over speaks in grand terms about the project, its scientific framing, and its radical potential for planetary change. It has less a leafy, arboreal vibe of vigorous plant life and more a techno-infused aesthetic where radical science meets futurist vision. The plants – tobacco and thale cress - appear pruned, disconnected from one another, each sitting within its individualised plot within the pipe infrastructure. Several small test tube vials hang within the branches of these minimalist plants, with some containing synthetic DNA holding a few kilobytes of digital data. In preparation for the installation the team had created these digital files (including gifs and small sections of poetry) with the idea of storing them in, and retrieving them from, the plants (adopting

the same genetic engineering techniques that MISL lab's research paper explored). However, in using the nanopore sequencer to decode the data (as described in the research paper) it became clear that the 'times of decoding' and the 'times of the exhibition' were out of sync. Decoding the data each time a visitor arrived to view the installation became untenable given the lengthy time per download (between eight and twenty-four hours). As a result, they adopted a somewhat less cutting-edge procedure, storing the synthetic DNA in vials on display within the branches of the plants. As such, visitors experienced the installation at different junctures in the process of 'downloading' the digital data. Once the data had gone through the long process of being read by the sequencer, it was sent to 'Touch Designer' – a node based visual programming language – which interpreted the data and ran an animation sequence displayed on a screen at the center of the installation (the gif or poetry that had been uploaded at an earlier point in time).

Ethical limits, gaps, and absences

In one sense, the critique this collaboration brings to bear on the environmental ravages of digital capitalism is well known. But their interventionalist response to this critique is less so. They do not, for example, explore the somewhat oversaturated pathways of green transition thinking: the pursuit of decarbonisation strategies or more sustainable mineral extraction practices. Nor do they venture into degrowth or post-capitalist terrain: the pursuit of a radical re-scaling of the role of the digital in our lives. What they do envision is an alternate planetary-digital-knowledge nexus where the environment becomes more than that which enlivens the digital (its minerals, materials, resources, and so forth). Or where the digital becomes more than that which mediates environmental knowledge and action. More radical still is the envisioning of the environment and the digital as folded together. And not in any metaphorical sense. In such a folding, various living organisms *become* speculative technologies (Hong, 2020) of data storage. But such an enfolding is far from unproblematic. This is a form of programmability that is clearly more penetrative than the imaginaries emerging from either the 'internet of nature' (Galle et al., 2019) or the 'internet of trees' (Gabrys, 2020).

One obvious counter-critique to such collaborations is that in their desire to find a technicalised means of addressing a planetary wide problem – organic storage devices that sequester rather than emit carbon – they reproduce some of the same logics of extraction that epitomise our current predicament. If the histories and legacies of the climate emergency are embedded within a Euro-American desire to conquer and colonise the planet's resources at will – evidenced in the countless, and all too familiar, narratives of empire (Haraway, 2016; Moore, 2016; Lowenhaupt Tsing, 2015) – then asking in what sense such projects are dissimilar is a legitimate question. If the colonising logics of extraction have envisioned the environment as but a set of resources to be harvested in order to, at first, build 'civilisation,' then what does it mean to invoke the same logics in order to putatively save it? Anthropologist, STS, and Indigenous Studies scholar, Kim Tallbear (2013a, 2013b) has written very persuasively on these questions. Tallbear (2013: 31) emphasises that it is very difficult to understand Native American DNA outside its rootedness in colonial biomedical practices. For her, indigenous categories are co-constituted with U.S. race categories – themselves co-produced within Euro-American colonial practices. The scientific 'gaze' that accompanies such practices, she argues, mobilises DNA as a technology that disconnects it from the lived relations of the bodies, peoples, and lands that constitute it. The stories that emerge from Tallbear's work speak to the histories of appropriation of native biological resources for the interest, use, and gain of western scientific practice (Tallbear, 2013a: 202). Genomic mapping is, she implies, an enterprise premised on a particular form of 'biopiracy' or 'biocolonialism' where the stewardship of human and nonhuman biological materials draw us into complex ethical terrain (Tallbear, 2013a: 192–193). Tallbear's work reminds me of the question of stewardship of non-human others. For example, as we learn more about the (near magical) mycelial networks through which interspecies forest communities live and thrive – the 'wood-wide-web' (Steidinger et al., 2019; Popkin,

2019) – what does it mean to speculate about their instrumentalisation as storage devices for digital data? In this sense, and as Tallbear suggests, the question of ethics is central to DNA worlds and the speculative collaborations they engender. Both in terms of the ethics explicitly articulated *through and by* such collaborations as well as the ethical reflections that can be gleaned *about* them.

It was the histories and legacies of GMOs – particularly through their deployment by organisations such as Monsanto and Bayer – that became a clear point of critique by some of those who attended the installation, with some visitors explicitly querying the *right* to manipulate plants in this way. The collective's response was to embrace such critique as an expected outcome of their speculative method and to incorporate material on ethics within the installation. Articulating an 'ethics first' approach, the *Data Garden* instantiated the idea that ethical reflection should always be part of new technology development (Reijers et al., 2025). Residing within the texts accompanying the installation is a concern for the collectivities that generate, access, own, and care for data. The *Data Garden* is offered in stark contrast to the surveillance-saturated logics and practices of contemporary data capitalism. Here the ethical vision is one of small, localised collectivities tending to their data *as gardeners*. The focus is on an ecological ethics of care: caring for emerging relationships between people, organisms, and technology across species boundaries as eco-tech relations are rewired for the good of the planet. Such ethics materialised through engagements with visitors on multi-species consent (plant permission) as one form of doing ecological ethics, as well as spaces of discussion with synthetic biologists on their methods and epistemologies.

The position from the synthetic biologists at MISL – incorporated within the installation's materials – is that digital data modifications within an organism *should not* affect its appearance or behaviour. If we return briefly to MISL's research paper, we will recall that researchers engineered E. coli with CRISPR enzymes CAS1 and CAS2. And that such CRISPR proteins are said to 'grab' free-floating pieces of DNA within a cell and integrate them at a precise, yet 'safe', location within an organism's genome (Shipman et al., 2017, Meiser et al., 2022). So, while various parts of a given genome govern specific functions, synthetic biologists speculate that certain genomic spaces remain 'empty' or 'vacant', and hence, are imagined as safe places to inject synthesised DNA. The inference here is that these 'vacant' or non-coding spaces of an organism do not have any reproductive role to play, and hence, do not affect the organism's life cycle, behaviour, or appearance. As the limited experiment conducted by MISL researchers showed, a digitally encoded E. coli genome could be replicated over forty generations lasting a duration of seven days. But it is important to say that such 'vacant' spaces are constructed at the edges of scientific understanding, or more particularly, at the limits of scientific knowledge making. But the further one approaches the horizon of such knowledge making, the more indeterminate (Alexander & Sanchez, 2020) things become.

In reimagining the planetary-digital-knowledge nexus, this collective works as an ethico-speculative knowledge making form: it provokes ethical reflection on 'not-yet' planetary futures and in doing so makes visible the more speculative practices that inhabit the work of synthetic biology. Such practices take form as knowledge gaps and limits at the edges of the discipline's understanding and are imagined in particular ways. And such imaginaries inflect ethics as a particular type of concern: in this case, what is currently unknown at the intersection of CRISPR enzymes and digital data is *speculated* as being 'empty' or 'vacant'. But such linguistic forms while operating as placeholders for epistemological indeterminacy – that which is unknown or unknowable at this juncture in time – are not ethically indeterminate; that is, the ethical questions that such language gives rise to are neither neutral nor unknowable. In fact, 'empty' and 'vacant' perform an ethical operation that enact these coding spaces as non-harmful. As such, they signal that there is 'no need for concern', and in doing so constitute ethics as a non-issue. This is less an *absence of ethics* and more an *ethics of absence*. Epistemological indeterminacy, in this case, is, therefore, saturated with ethics. Such indeterminacy is filled in by semantic forms that do ethical work, albeit significantly reducing the

force of ethics at the expense of speculation. It is here that some of the more difficult questions on the ethical concerns of speculative techniques and collaborations come into view. What we see in operation here are sets of speculative knowledge practices that work by imagining future states through contemporary limits or gaps in knowledge practices (via experiments and prototypes that rehearse 'not-yet' futures). In doing so, I argue, they enact an ethics of absence. What, then, does this imply for thinking about more radical planetary propositions such as these? What type of ethical practices might be up to the task of such speculative knowledge making?

The answer from the collaboration is layered. As mentioned earlier, it is GYOC that speaks mostly to the question of ethics on behalf of the collective, articulating an 'ethics first' approach. In principle, this implies embedding ethical concerns within the design of emerging technologies: something they practiced through interactive (and iterative) engagement with visitors, taking account of 'ethical issues' along the way and incorporating them into the installation through various materials. What they foreground is an ecological ethics of care, a set of understandings that focus on practices of care within emerging intra-species relationships (humans, living organisms, and technologies) for 'the good of the planet'. But such practices are entirely dependent upon the knowledge forms produced by synthetic biology, which, as we have seen, veer towards an ethics of absence. In this sense, then, the term care becomes boiler plate language[1] for a set of considerations that are somewhat removed from the complex knowledge practices of synthetic biology. Here, care only becomes meaningful as intra-species relating if the epistemological-ethical renderings of synthetic biology make sense. In signaling that digital data DNA modifications to organisms are not harmful, the burden of care is significantly reduced as the force of ethics recedes in the rear-view mirror of speculation. When confronted directly with how such knowledge gaps are rendered through forms of speculation and the ethical significance of such a move, MISL members of the collective adopt a boundary making approach (Star & Griesemer, 1989), positioning ethical concerns as beyond the problem space of their research. Here, a scalar distinction is made between the biological and the molecular. In their rendering, the biological – understood as living organisms – is owed, in some shape or form, a duty of ethical care. The molecular, on the other hand, is rendered as a substrate of an inert system, and, therefore, beyond the pale of ethical reflection. So, while care is explicitly articulated by the collective, it emerges at the intersection of their practices and at the limits of their understandings. It is here that it becomes vulnerable as a concept; subject to the hierarchies embedded within speculative constellations. And this is a particular challenge to how feminist renderings of care are taken up in the world and translated into different settings. While much work in STS, and particularly feminist STS, has shown that caring practices need to be located within our methods and epistemologies (Puig de la Bellacasa, 2017; Schrader, 2010), what we see through the lens of this particular case is a set of speculative epistemologies that produce ethics in such a way that its force of care is curtailed. Postulating no harm – the manifestation of an ethics of absence - diminishes care to a discursive form, a figure bereft of its epistemological scaffolding. MISL's clear-cut distinction between the biological and the molecular lacks a sense of doubt about the knowledge constructs that are being mobilised. And doubt, as various philosophers over time have argued, is a central force of ethical practice. From Emmanuel Levinas (1969) to John Dewey (1922), to Simone Weil (2021), doubt is characterised as that which interrupts or suspends self-certainty: the point at which one becomes open to others. In other words, it is a moment through which ethical relations, and their obligations, can emerge.

Conclusion

In *On the Emergence of an Ecological Class: A Memo*, Bruno Latour and Nikolaj Schultz (2022) ask why ecological movements have been unable to mobilise more effective coalitions for planetary futures. Part of their answer is to point towards a conceptual impasse, and particularly, to how the political architectures of western modernity are infused with concepts (growth, progress, and develop-

ment) that are not up to the task of envisioning more radical alternatives.

This paper has taken a different approach, examining the recursive relations between planetary materialities, digital infrastructures, and environmental knowledge making: the planetary-digital-knowledge nexus. The argument here is that this nexus produces a set of conditions (overlaps, interdependencies, complicities) that make critique of, intervention into, and envisioning for, alternate planetary futures difficult. In examining a collaboration for planetary futures, the paper teases out one radical vision that does not try to position itself within this nexus, but that reimagines it entirely. Focusing on *The Data Garden* installation, the paper argues for thinking about this collaboration as an ethico-speculative knowledge making form. One that both provokes ethical reflection on 'not-yet' planetary futures, while at the same time making visible the forms of speculation that inhabit the scientific practices of synthetic biology. Speculation, in this sense, is what conjoins synthetic biological practice with forms of design oriented futuring work. But it does so in a way that invokes a series of ethical questions. And while the collective explicitly addresses these ethical concerns, it does so by taking an ethical stance that produces what I have called an ethics of absence. Not an absence of ethics, but a means of doing ethical practice that, in some sense, puts doubt into abeyance and diminishes the force of ethics. In other words, the problem space that the collective inhabits enacts ethics through the speculative epistemologies of synthetic biology. In doing so, uploading digital data in the form of synthetic DNA is deemed 'safe'. That is, it is not seen to harm the reproductive (or other important) functions of the host organism. This enables the collective to postulate an ethics of care. But not in any cynical sense. GYOC, in particular, are committed to *thinking with care*. The epistemological force of synthetic biology, however, is such that care is truncated, becoming merely a means of talking about intra-species relations that are, already, predicated on a lack of harm.

In *Genomics with Care*, anthropologist and STS scholar, Mike Fortun (2023) describes various modalities of care (curation, scrupulousness, solicitude) that geneticists work with and through. And such modalities are acknowledged as arising at various limits within their scientific practices, limits that produce "insight and blindness simultaneously" (Fortun 2023: 201). It may well be that this paper has an eclipsed ethnographic viewpoint that has engaged the limits of scientific practice through its blindnesses. Nonetheless, it raises important questions about the ethics that are enacted through such radical speculative projects.

What this article has been pointing towards is that the work of critically engaging with the contemporary moment is fraught with difficulties. Given how 'good' capitalist forms are at appropriating critique, the spaces for building more radical planetary futures remain limited. It is here that speculation has come to play an important role: as method, as intervention, and as critique (Wilkie et al., 2017). In one sense, speculation attempts to 'escape' the gaze of capitalism by postulating a non-appropriated outside from which to build its critical propositions. Unleashed from such constraints, it (ideally) affords new publics the means to imagine new worlds. But speculation itself also requires sustained critical engagement (revealing yet another layer of critique making) in order to address the grounds upon which it produces its own visions (and possible blind spots). What this article makes visible is how ethics oftentimes remains a blind spot for those experimenting with speculation. Its insight is not that technologists, futurists, and those who dare to make radical propositions do not consider ethics as important to their work, they clearly do. But what oftentimes emerges as 'the ethical' in these spaces is a type of boilerplate language that ascribes various forms of ethical theory (an ecological ethics of care) and method (ethics first) to complicated and hierarchical constellations (in this case collaborating with synthetic biologists). In a sense, then, ethics is simultaneously centered and decentered within speculative practices. On the one hand ethical methods and theories continue to be explicitly articulated and cultivated. Yet, on the other, the force ascribed to ethics clearly reduces its valence. What needs more attention are the modes of doing ethics in situ: an opening up of speculative spaces – both explicit (speculative designers) and implicit

(synthetic biology) – to an understanding of ethics as a set of dynamic and situational concerns (Keane, 2015, 2024; Zigon, 2024) working across the planetary-digital-knowledge nexus. While proposing future planetary visions is bold and radical work, what is needed, it seems, is far more radical ways of imagining and doing future ethics.

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Notes

1 Thanks to anthropologist Ilana Gershan for this term.

Sustainable AI Research? Three Approaches Within High-Performance Computing Research Communities and a Critique from the Margins

Anne Pasek

Trent University, annepasek@trentu.ca

Brian Sutherland

University of Toronto

Abstract

High-performance computing research, particularly concerning so-called artificial intelligence, is increasingly scrutinised for its environmental impacts. Many researchers are actively debating how to respond. Surveying recent English language research community publications, this paper identifies three distinct but overlapping proposed approaches to greening compute-heavy machine learning research: 1) efficiency, 2) the net benefit of downstream impacts, and 3) virtuous competition through environmental metrics. Alternative, and much more radical, proposals can be found in a small but growing contingent of scholars who seek to 4) subordinate research questions to planetary limits. Each approach is more than merely technical, with significant considerations given to researchers' social incentives and relational commitments to one another. Nevertheless, all approaches are constrained by limitations in enumerating compute and mobilising social incentives. This article assesses tensions across these approaches and concludes by connecting them to wider discussions on the constitutive and increasingly planetary character of method in STS.

Keywords: AI, Research Methods, Sustainability, Environmentalism, Climate Change, Epistemic Virtues

Introduction

The climate impacts of research are a growing site of social concern. While early iterations of these debates focused primarily on the outsized role of air travel in the circulation of scientific knowledge (Berné et al., 2022; Katz-Rosene & Pasek, 2024), the rapid rise of big data and machine learning research (often packaged as 'artificial intelligence' or AI)[1] has brought the environmental implications of high-performance computing under new scrutiny. The training stages of cutting-edge neural network models, for instance, typically require hundreds or thousands of hours of energy-intensive computational work, located in data centres hosting unprecedentedly large datasets, and potentially spread across multiple geographic regions (Bian et al., 2024). This results in significant climate and water impacts. Simply training OpenAI's now-outdated GPT 3 model, with its estimated 175 billion parameters, may have produced 552 tonnes of CO_2e emissions (Luccioni et al., 2023), the equivalent of driving more than 100-gasoline powered cars for a year. A conversa-

tion with ChatGPT, a recent study concludes, consumes roughly the equivalent of a 500 ml bottle of water (Li et al., 2025).[2]

While these figures have been highly circulated by news media, posing public relations challenges for tech companies, the problems that they index have also generated significant and unresolved debates within compute-heavy research communities, on their own terms. Although current practices in the field are generally understood to be unsustainable by practitioners (Michael et al., 2023), there is as yet no consensus on what sustainable compute-heavy machine learning research would look like, nor how it should be achieved. At times, scholars have advanced this project through personal reporting, with some researchers including the carbon emissions of their computationally-demanding modelling work in their academic papers as a matter of ethical disclosure (Wu et al., 2022; Zhang et al., 2022). Other researchers have drafted preliminary green guidelines that might scale up to more collective or structural changes, including early open source guides (The Turing Way, 2022), sets of principles and best practices (Lannelongue et al., 2023; Nazaré et al., 2023; Schwartz et al., 2019), and calls for formal guidance from funders and regulators (Bashir et al., 2024). In so doing, these interlinked communities are beginning to articulate early questions and approaches that may come to define a new epistemic virtue around climate-informed modes of computational work and scientific practice: one where 'good' research is 'green' research. This paper offers a map of emerging and at times conflicting approaches to achieving this goal.

'Epistemic virtues' are a key means to this end. They describe normative moral commitments that are internalised and practiced by individual researchers within scholarly communities. They are a shared sense of what exemplary knowledge production should look like, and how knowledge production articulates across both inner dispositions and external conduct as well as individual values and incentives versus collective outcomes (Uygun Tunç & Pritchard, 2026). They are a key part of wider epistemic cultures that characterise global research fields or regional communities beyond simple disciplinary identifications (Knorr Cetina, 1999). Epistemic virtues have histories, intersect and travel across different disciplinary fields in different ways, and tend to accrete and overlap rather than sweep each other aside in grand paradigmatic reversals (Daston & Galison, 2007: 18). Within and beyond scientific communities, they must be cultivated, argued, taught, and internalised (Van Dongen & Paul, 2017). The 'how' of the research is as important as the research outputs to this end because method is understood as constitutive to the membership and character of a field.

These themes are deeply germane to both long-standing and recent questions in science and technology studies. In addition to investigations of how politics are socially admitted or bracketed from the domain of scientific practice, and the relatedly social implications of given technical modes of measuring the world (Porter, 2020[1995]; Shapin & Schaffer, 1985), the intersection of epistemic virtues and sociotechnical accounts may also extend to more contemporary theoretical investigations of the role of infrastructures (Jensen & Morita, 2015) and environments (Goldstein & Nost, 2022). In the context of constraining energy, water, and mineral supply chains (Cooper, 2023; Hogan, 2015), shifting orientations towards the indexicality and uses of data (Alvarado, 2023; Bender et al., 2021), and a deepening climate crisis (Mollen et al., 2026; Pasek, 2019), data infrastructures provide an increasingly important foothold into questions of technoscientific power and practice – and thus potential debates around in-group norms and ideals.

As this article demonstrates, high-performance computing practitioners are themselves actively debating such questions. The distinctions and boundaries of potential green machine learning virtues are not yet fixed, nor is it clear how such things might coexist with previous models of 'good science.' Participants in these conversations call on often contradictory and incongruent theories of change and moral conduct when articulating what sustainable machine learning research methods might be and how to bring them about. Moreover, the empirical fact of the emissions intensity of a given action in a digital network – such as the carbon footprint of storing a terabyte of data for a year, or that of a training run for a neural net – is often up for debate, owing to unsettled methodological tensions in how

the carbon footprint of a discrete action within a digital network should be disaggregated and assessed (Pasek et al., 2023). This makes it more difficult to calibrate degrees of concern and urgency across scholarly (and more than scholarly) communities, and to cohere emerging ideals into practice. It also brings the ostensibly distant figure of the dispassionate scientist into new proximity with contestations around the political economy of the cloud, as well as the climate trajectories of the wider information and communications technology (ICT) sector and struggles for social equity measures within and beyond the university.

This article assesses the state of this internal conversation by surveying recent academic and grey literature publications within compute-heavy machine learning research communities forwarding collective environmental ideals and strategies. Building on previous analyses of 'sustainability' as an underdetermined and contingent site of meaning making and political struggle (Alaimo, 2012; Vaughan et al., 2023), we explore how these efforts are framed as both technical problems and questions of more-than-technical social coordination. In other words, to dismiss these efforts as mere technosolutionism, even if one finds limitations in the scope or likelihood of their climate mitigation potential, would be to miss the important analysis this community is offering about itself as a community, and the group relations and pressures therein. Such a gesture would also overlook the interesting ways in which these social analytics are entangled in ever-more planetary scales of scholarly actors – both human and non-human – and thus decisions about whether and how to admit or obfuscate these networks in proposals for environmental action.

We describe three common and overlapping strategies in the mainstream machine learning research literature – relative efficiency, net benefits, and peer competition through green metrics – and analyse the strengths and limitations to each, both in terms of technical feasibility and the social affordances they point to within their fields of study. We then contrast these approaches with a degrowth ethos that can be found in an emerging 'radical flank': a small but growing set of researchers interested in subordinating the question of computational design to that of planetary limits. In contrast with accounts of past epistemic virtues (Daston & Galison, 2007), we show how emerging strategies for forwarding green high-performance computing are largely predicated on the social composition of the research community as a group, driven by relational rewards and constraints, rather than as a matter of individual dispositions. This analysis leads to a concluding discussion of the constitutive character (and carbon intensity) of research methods more broadly, bridging insights from science and technology studies to better explore how emerging digital environmental practices might forge both different kinds of social research cultures and different kinds of planetary configurations made in and through research.

Literature review

Epistemic virtues can provide a particularly useful analytic foothold for science and technology studies (STS) scholars looking to parse the interrelations between technical and social systems. While the field takes the presence and influence of these connections as both a foundational given and an enduringly important object of study, many scientists themselves have at times been reluctant to acknowledge such influences, for fear that doing so would threaten the dispassionate and apolitical character of an imagined objectivity (Harding, 2015). This tendency can be particularly acute in computer science, where formal structures of abstraction (Golumbia, 2009; Malazita & Resetar, 2019) and the bracketing of ethics as a tertiary concern in computer science education (Darling-Wolf & Patitsas, 2024) frequently serve to deepen an imagined disconnect between the design of digital systems and their socio-material outcomes – especially in the domain of 'pure' research. Yet, as STS scholarship has long affirmed, such boundaries are harder to maintain during periods of shifting epistemic foundations (Shapin & Schaffer, 1985). Debate admits internal advocacy within expert communities, self-reflection about how a discipline's political and material orders are organised, and theories about how to change them.

Contemporary environmental concerns broached within the research community, and the

ways they cut across previously assumed spatial, temporal, and social boundaries that separate the researcher and the researched, may serve to accentuate this tendency. When the techniques of knowledge production contribute to the environmental problems researchers are trying to isolate and understand, scholars will find themselves – often uncomfortably – within the frame of what they are studying. In this way, considerations of the climate impacts of the research process can provoke ethical and epistemic challenges to the straightforward pursuit and dissemination of knowledge from a position of remove, and through any means (Knox, 2020). The result can be both new forms of responsive activism within expert communities (Anderson, 2013) as well as efforts to refuse these demands and maintain previous community norms and practices (Bendell, 2016). No given outcome is guaranteed from these moments of destabilisation, but they do provide provocative calls to reassess the boundaries between researchers, research infrastructures, and the material benefits and harms they distribute across the world.

Researchers in the social sciences and humanities are not exempt from these dynamics. A growing body of work on Anthropocene questions, the energy humanities, and climate history has also provoked positional reflections in a range of fields, including STS (Latour, 2004; Puig de la Bellacasa, 2017), history (Chakrabarty, 2009), literature (LeMenager, 2014), media studies (Peters, 2015), and anthropology (Knox, 2014). This work's redoubled emphasis on the causal importance of macro-scale material forces—whether oil, climate systems, or geology—frequently point to the role environments can play as a third axis modifying accounts of socio-material inter- and intra-actions. In some schools of thought, the figure of the 'planetary' helpfully encapsulates this analytic (Clark & Szerszynski, 2021). As argued elsewhere in this issue (Çelik et al., 2026), planetary analyses of knowledge formation challenge the sufficiency of both ontologically flat actor-networks and socio-technical dyads. Instead, taking planetary processes seriously requires a multidimensional accounting of entangled relations across inequitable social groups, global locations, and geophysical potentials and harms. It is to grapple with the fact that all researchers are enmeshed within the worlds they seek to describe, with shared (if never equal) relational responsibilities and consequences across the work of knowledge formation (and effects) that are simultaneously social, material, and planetary.

Computer Science as a whole has yet to fulsomely grapple with the planetary, having (understandably) first taken global data infrastructures as a collective accomplishment rather than a cause for ethical self-interrogation (Edwards, 2010; Ensmenger, 2013). The development of abundant and personal compute resources is a story of increasing accessibility, with career stages playing less and less of a role in mediating the finite use of research machinery (Hu, 2015). This access story is not complete, however, with enduring Global North/South divides characterising the availability and performance of both vernacular digital tools (Shahjahan & Niloy, 2026) and specialised compute infrastructures (Lehdonvirta et al., 2024). With the growing importance of scale and cutting-edge graphical processing units (GPUs) in machine learning research, moreover, progress on research infrastructure accessibility may be backsliding along with the climate targets and efficiency measures that characterised previous periods of digital industry self-governance (Pasek, 2023).

A planetary analytic, taking stock of local material constraints, meso-scale social group formations, and macro-scale environmental pressures, therefore has increasing salience to accounts of compute-heavy research. As we describe below, there are indeed moments where debates in the field bend in this direction. In the face of spiralling compute costs, carbon emissions, and public critiques, machine learning researchers have good cause to think about human and non-human planetary relations and the role of both in-group incentives and external environmental constraints in adjudicating new styles and sensibilities of being a high-performance compute researcher. Yet, as previous examples stress, these openings also come with anxieties, sacrifices, and reactionary efforts to prevent hierarchical destabilisations or even minor headwinds in the pursuit of knowledge. As such, this paper seeks to parse how different voices within the field's centre, or alter-

natively commenting from its margins, propose new settlements in the figure of green research along both social, material, and planetary lines. Reading with voices from the field, we ask: what kind of problem should climate change be to the field, and what new kinds of epistemic virtues and relational commitments could help resolve that challenge?

Four approaches to sustainable high-performance computing

This paper's assessment is distilled from reviewing a corpus of over 60 articles and white papers, published between 2018-2024, that address the question of green epistemic virtues from within English language machine learning (or so-called 'AI') communities. These texts were assembled through a combination of digital literature searches, informal recommendations from practitioners and co-panellists at public events and conferences, and tracing relevant citations in bibliographies. Based on the centrality of these texts within citation networks and major research institutions, the corpus represents a significant portion of the influential work published on this topic, but does not attempt to be exhaustive in scope or totalising in its claims. Instead, the analyses that follow were formed through interpretive content analysis with the goal of identifying common heuristic patterns and exemplary arguments about unsettled empirical and ethical questions in the field. It thus offers more of a social cartography (de Oliveira Andreotti et al., 2016) than a meta-analysis.

For each section, we begin by describing the proposed approach through one to two exemplary cases, and then discuss the mechanisms by which the approach seeks to achieve its technical (questions of definition, measurement, infrastructural design and utilisation, etc.) and social (questions of attention, prestige, opportunity, and training, etc.) ends. By splitting these different means and motivations apart in our analysis, we aim to better demonstrate overlapping appeals and pressures in differing socio-material accounts of digital sustainability—how each approach to green epistemic virtue articulates simultaneously across technical and community relations. We also aim to stress how planetary concerns threaten to complicate both sides of this sociotechnical dyad (for instance, in the differential global distribution of renewable energy resources, or enduring Global North/South prestige asymmetries) and are variably rhetorically mobilised or bracketed from the framing of solutions. Each section concludes with our assessment of internal limitations to these proposals and external barriers to their enactment.

Environmentalism through relative efficiency

Often the first approach to mobilising around new problems of practice is to draw clear distinctions between favoured and disfavoured conduct. Schwartz et al.'s highly influential intervention (2019) does so with admirable simplicity by splitting so-called artificial intelligence research into two basic categories: Red AI and Green AI. This intervention well characterises the broader emerging uses of efficiency as a potential green epistemic virtue for the machine learning research community.

Red AI is defined as any research effort that privileges the accuracy of deep learning models as the sole metric of success. Researchers today typically pursue this goal by means of exponentially increasing the compute resources (in both datasets and training time) they use in model construction – in effect, a brute force approach to get better results. Schwartz et al.'s survey of deep learning papers published in central journals to the field from 2013-2019 demonstrates a worrying dominance of Red AI trends through a 300,000 fold increase in compute over this time – a rate that exceeds that of Moore's Law (Schwartz et al., 2019: 56). Because Moore's Law provides a somewhat predictable pace for energy efficiency improvements in wider ICT industry infrastructures (Pasek, 2023), rapid leaps forward in research infrastructure requirements represent a distinct and worrying environmental trajectory: the field is getting dirtier faster than the industry is getting cleaner.

Green AI, conversely, would be any form of machine learning research that breaks this trend, and so does not require exponentially greater amounts of compute resources to produce novel results (Schwartz et al., 2019: 59). Ideally, this environmental approach would go so far as to reduce, rather than just maintain, current computational

requirement rates, but definitionally Green AI is simply understood as any project that uncouples the strict correlation between academic success and resource expenditure – that eschews a brute force approach. It is thus an orientation towards conservation through process efficiency, rather than a commitment to meeting absolute targets or an articulation of particular conditions of sufficiency, that separates Red AI from Green AI. It suggests that sustainability can ultimately be determined through relative measurement.

Understanding sustainability through efficiency has its social advantages. The Red vs. Green designation provides a usefully clear conceptual intervention and provocation (the paper has been cited more than 3,000 times at time of writing). It also allows for a moral defence of machine learning research's past, in tandem with a critique of its future. Red AI, Schwartz et al. (2019: 54) are at pains to emphasise, "has been yielding valuable scientific contributions to the field"; the only problem is that "it has been overly dominant." By arguing simultaneously for a relational boundary between sustainable and unsustainable research practices, and by seeking only to adjudicate the relative distribution of each, it both brokers space for action and accommodates a plurality of approaches. Projects pursuing benchmark improvements at any cost are still potentially welcome, just not as the sole direction of the field. In this way, past epistemic virtues can coexist with emerging green ones, in a range of favoured scientific practices. This may pre-emptively defuse potential critics who remain committed to Red AI approaches, or are at least apt to object to a condemnation of both their extant research methods and research products. Similarly, by allowing researchers to respond to climate imperatives with quantitative precision, via a range of mathematically-modelled efficiency algorithms (see, for example, Bian et al., 2024; Li et al., 2025; Silva, 2021), this approach allows for familiar tools to be brought to bear (unlike the rather more qualitative issues with algorithmic gender, racial, and disability bias that the field continues to struggle to navigate).[3]

The relative efficiency approach also allows for proponents of environmental reforms to make arguments about the social impacts of exponentially increasing resource needs within the composition of the research community. This too can be strategic; if environmental and social concerns are aligned, then a greater global coalition of interested parties might be rallied to the cause of greener research norms. In the account of Schwartz et al. (2019: 56), Red AI represents such a threat in so far as it has come to define the field, "through the use of massive computational power while disregarding the cost – essentially 'buying' stronger results". The Red AI, brute-force approach can produce diminishing returns – a 10-fold increase in deep learning model performance may require as much as a 10,000-fold increase in compute resources (Thompson et al., 2021) – which effectively prices out junior and Global South researchers who lack access to institutional or grant-subsidised compute clusters (see also Bender et al., 2021; Strubell et al., 2019). It also potentially diminishes the role of creativity in research, rendering research advancement, to a degree, as another 'pay to publish' game with a computational processing twist.[4] Moving against this trend, conversely, would potentially lower barriers to entry and better value the cognitive ingenuity of researchers. As the authors write, "we want to shift the balance towards the Green AI option—to ensure any inspired undergraduate with a laptop has the opportunity to write high-quality papers" (Schwartz et al., 2019: 54). This appeal to the future of the discipline, cast in the face of a young and deserving student, can thus be read in jointly moral and environmental terms (even if said student is themselves not primarily motivated by the environmental call to action). The epistemic virtue here therefore adheres to group norms and outcomes, not individual moral values or judgements.

Shared social coordination, as well as flexible horizons for the achievement of green ends, are thus both rhetorical and practical benefits that a relative efficiency approach – rather than restrictive targets or caps – offers in adjudicating the definition and trajectory of sustainable research methods. It suggests that the problem of climate change for machine learning researchers is one that demands collective coordination and that is simultaneously implicated questions of academic equity yet can ultimately be addressed through technical means that mitigate these parallel relational and planetary pressures. Infrastructural

expenditures drive these questions forward, but in ways that may ultimately be resolved at the scientist's desk, if enough coordinate to do so.

There are, however, practical downsides to using relative efficiency to guide this discussion. Framing the question around the ratio between computational inputs and outputs risks ignoring material complexities that extend beyond the discrete performance of a given compute cluster at a given moment in time. By some estimates, 66-75% of the energy needs of a model come from the sundry work of inference and data management and storage, not use or iterative refinement, bringing a singular emphasis on model training efficiency into question (Luccioni et al., 2023; Wu et al., 2022). In other instances, being strategically selective about the kinds of metrics (and best-in-class infrastructures) can seemingly counterbalance the exponential consumption concerns of Red AI (Patterson et al., 2022). Further questions have been raised around the wider sectoral build out of data centres, and the extent to which the promise of data-intensive applications and research agendas both outpaces, and induces, demand (Hogan, 2021). There are also growing concerns about potential rebound effects, whereby increases in the efficiency of a resource makes it less precious, and thus apt to be used more in aggregate (Lannelongue et al., 2023). The politics of infrastructure, especially at the fenceline or through regional grids that host data centres, is not especially legible in this approach. A future full of machine learning tools and datasets that no longer outpace Moore's Law could still be one with growing aggregate energy demand and worsening environmental impacts. In such instances, models of sustainability exclusively developed through relative resource consumption rates internal to the research community may prove inadequate to the task of assessing and leading a way through the planetary problem. They may, to the contrary, obfuscate it (Cellard et al., 2025). Green AI, after all, isn't actually green; it's just less red.

Being green, on balance

The ethos of efficiency that characterises Green AI combines with an emphasis of social impact accounting in the second approach that we highlight. This school of thought draws different boundaries around where the adjudication of sustainability can be said to begin or end. By considering the wider effects of compute-heavy research when deployed in the world, researchers and advocates can more effectively assess its net effects. As such, instead of creating a conceptual cut between favoured and unfavoured scientific conduct, the net effects approach advocates that all research, overall and on balance, should be green. Importantly, this provides a way of sanctioning research efforts that are themselves highly resource intensive and even relatively inefficient, but which have overwhelmingly positive downstream environmental benefits.

The Royal Society, an organisation representing UK scientific interests, exemplifies this approach in a report that was developed out of several workshops about digital knowledge production and emerging technologies facilitated between researchers, government, and industry (The Royal Society, 2020). Highlighting both the potential benefits and harms of compute-heavy data products and programs of inquiry, the report urges considerations of "energy proportionality" in the moral and administrative judgements of digital research processes and outputs, and further calls for regulators to develop guidance to these ends (The Royal Society, 2020: 80). This echoes a larger trope in the literature (Kaack et al., 2022; Luers et al., 2024) and public discussions (Lohr, 2024) that sees machine learning tools as a double-edged sword (Cellard et al., 2025): a catalysing set of technologies that may result in both hazardous and utopian outcomes, and as such requires sober and skilful oversight.

Proportionality implies a measured consideration of the costs of training, constructing, and using digital resources against the potential energy or carbon savings that an application might enable. For example, an algorithmically-controlled building heating and cooling management system may be very resource-intensive to train and run, but could potentially enable considerably more emissions reductions over the course of its lifetime. Alternatively, a high-performance computer system may not reduce emissions, but its development could nevertheless still be considered sustainable and ethical through a combination of compensatory carbon offset purchases, green energy procurements, and perhaps even

social equity measures. A tacit net zero calculus is afoot here, with the positive impacts of a technology's application all roughly imagined to count against the climate (or social) harms of the research and technical development process. This calculus, however, remains largely figurative; the Royal Society report declines to name specific examples in which energy proportionality has not been achieved, with the sole exception of Bitcoin (The Royal Society, 2020: 81).[5]

A figurative accounting approach is also a social proposition. By highlighting intended long-term positive outcomes alongside harmful intermediate means, the net balance proposition emphasises researchers' best intentions and future redemptive possibilities while potentially palliating anxieties about the unsustainability of compute-heavy technology as a whole. It also reduces the potential for individual researchers themselves to be judged harshly for their work, positioning them merely as the developers of 'tools' whose effects will be largely determined by "the context in which they are developed and deployed" (The Royal Society, 2020: 114). Researchers, in other words, can exercise responsibility but need not be held wholly responsible. This in turn sanctions the recommendation for governments to increase the funding of "high-risk, high-reward" data science and machine learning inquiry, based on anticipated if not wholly detailed environmental and social benefits (The Royal Society, 2020: 111). Here, again, a larger collective guarantees the production of epistemic virtues – one that includes more than just the research community itself.

This net impact approach thus has further implications for the relationship between researchers and the wider cloud industry. The work of sustainability, in effect, can be largely outsourced or externalised to the providers of compute resources and the remediators of e-waste rather than the designers and users of machine learning systems. Google researchers Patterson et al.'s (2022) set of sustainability best practices, for instance, emphasises the use of best-in-class infrastructures like Google's cloud network and the renewable energy and carbon offsets purchased by Google, Facebook, and Microsoft.[6] Google's environmental practices in its data centre design and load shifting work are further highlighted in the Royal Society report (2020: 78) along with calls for the industry to "lead by example" (The Royal Society, 2020: 5). In both instances, efficiency gains from researchers, combined with the green leadership of private industry, combine to potentially negate the problem of escalating digital climate impacts. This all serves to reframe the problem of climate change for the field as one of good and bad infrastructures, rather than good and bad research efforts. As a result, machine learning research methods can themselves be seen as largely neutral, rather than a key site of struggle towards different planetary outcomes. Put otherwise, green virtues can be deferred to compute providers and technological entrepreneurs; they perhaps need not be epistemic at all.

As in debates about relative efficiency, the net accounting approach also presents many practical and political limitations. For one, industry self-regulation is likely an insufficient strategy to get to truly sustainable compute infrastructures, however this might be defined. Flagship environmental data science projects are often subsidised by cloud companies as a means to win social license for broader data-intensive business strategies, rather than as a credible means of performing environmental governance within and beyond the sector (Espinoza & Aronczyk, 2021). A focus on providing advanced models and compute infrastructures to environmental and conservation scientists can also obfuscate more fundamental scientific needs for basic data collection in the field (Lukacz, 2022), especially in the Global South (Karlsson et al., 2007). What's more, under the semantic confusion of the category of 'artificial intelligence,' benefits specific to more narrowly scoped machine learning techniques are frequently used to justify the costs and impacts of more general purpose technologies (Joshi, 2026). Not unrelatedly, the ICT sector's absolute emissions continue to grow because of accelerating generative "AI" market bets, even within the ledgers of the industry's seemingly most exemplary corporate climate actors (Saul et al., 2024). State governance, in line with these aims, remains largely absent. Additionally, efforts to monitor and manage global climate and environmental impacts often ignore the continuity – or creation – of local environmental burdens and

frictions (Pasek, 2019; Sefyrin & Velkova, 2026), sometimes replicating familiar environmental racism dynamics (Bender et al., 2021: 613). Net benefits *for whom* remains an essential, though generally underexamined, question in such debates.

Additionally, while the emissions savings potentials of emerging big data technologies are highlighted extensively in defence of proportionality judgements, the field's parallel role as an accelerant of climate change is often not discussed to the same degree. Given the growing centrality of machine learning in new oil and gas exploration (Galaz, 2025: 42; Zero Cool, 2019), these are not trivial questions. They are also potentially incalculable—especially on the timescales that matter in weighing precautionary regulatory interventions. A recent attempt to outline a framework for assessing the present-day climate impacts of generative machine learning algorithms describes this work as a "seemingly intractable task," the difficulty of which "cannot be overstated" (Bashir et al., 2024). Speculative benefits and harms in the future represent yet a further order of difficulty – one that may be far more qualitatively than quantitatively thinkable, and thus will not reconcile with existing life cycle assessment frameworks (Kaack et al., 2022). Finding a usefully descriptive and expansive net impact number may ultimately not be possible. In this context, calls for proportionality guidance could risk deferring questions of research norms and regulatory action to further and future stakeholders that may not be equal to the task. As critics have argued, a focus on AI ethics in insular terms can ignore the wider consequences of the mass adoption of these technologies in terms of how power is distributed across companies, people, and the planet (Crawford, 2021).

Eco-competition

A third approach to green epistemic virtues is imagined to proceed through the promotion of best practices that all researchers should follow to ensure that they fall on the general side of sustainability. However, instead of setting general efficiency or net benefit criteria, this school of thought seeks to create new metrics and areas for comparison that grant prestige to a range of greener research approaches. Measurement, in this context, is both technically and socially relational. It implies that one can be ahead or behind the group (rather than merely in or out of a 'green' category), and that making these distinctions visible within communities of practice is key to effecting change. It thus suggests that the problem of climate change for the field is one that requires not only technical innovations but also forms of social competition.

Researchers imagine that new forms of awareness and incentives can be cultivated through multiple communicative channels internal to the scientific community. These include academic publications; several scientists (Lannelongue & Inouye, 2023; Rafat et al., 2023) have argued that carbon footprint estimates of machine learning research processes should be published along with new findings and models, reinforcing the salience of the climate issue within the research community and stoking healthy competition. Patterson et al. (2021) suggest that conferences might favour the publication of papers on efficient or small models in specific green tracks. Perhaps most famously, Henderson et al. (2020) argue for the creation of leaderboards to better track and evaluate progress in a research group, classroom, or wider field, and have released code on Github to facilitate this. Leaderboards are already a common feature of machine learning research, tracking performance across speed and size concerns. Adding carbon intensity to these metrics could be a simple technical means to stimulate a different kind of race.

This highly social model of environmental change seeks to harness peer pressure and scholarly recognition within the research community in order to better value more sustainable forms of compute-heavy inquiry, creating a "virtuous cycle where ML [machine learning] practitioners compete to… bend the curve of ML carbon footprint growth," (Patterson et al., 2021: 2). The eco-competition approach allows for flexible frameworks and comparisons. For example, given the range of relative differences between the carbon and financial costs of compute resources in different parts of the world, researchers may struggle to contract with the most efficient or environmentally well-provisioned set of cloud

providers. In such cases, they could choose to collaborate with researchers in other areas of the world who do enjoy such access (Lannelongue et al., 2023) or simply pick from alternative actions on a list of green tips.[7] Alternatively, researchers could simply publish their results, with the high carbon intensity of their local compute resources given as a caveat. In this way, even simply participating in the creation and publishing of carbon metrics can be read as an action – contributing towards social coordination and collectively altered norms (if not yet a direct carbon mitigation effect).

Like the previous two approaches, this eco-competitive outlook on sustainable heavy-compute research may also create grounds for inertia and contradictory outcomes. For one, even if the mass reporting of the energy and carbon costs of developing and/or running high-performance models became common practice, it doesn't immediately follow that accurate comparisons could be easily drawn across the heterogeneous contexts of different research architectures, nor that social pressure would be effectively mobilised on the basis of such accounts. There is no commonly agreed methodology for such calculations. There are, instead, many different ways of muddling through such questions, with significant trade-offs between accuracy and ease of use (Lannelongue et al., 2023). While the accounting protocols of some cloud compute providers, having more standardised data centres across different global locations, make it relatively simple to call the run time, and even energy use, of processors used to train a model, the carbon intensity of real-time, local grid power can often still be difficult to correlate (Lannelongue & Inouye, 2023). The Henderson group's leaderboard code, for example, is only compatible with a narrow range of systems and chips, and draws on data from Amazon Web Services that have not been independently verified. It is also the case that such narrowly cast assessments often ignore the larger lifecycle costs of manufacturing and maintaining equipment outside their window of use by a given researcher. In some accounts, the carbon footprint of model training can double when attempting to include these 'external' factors, inferred as they are from imperfect manufacturer disclosures (Luccioni et al., 2023). Further complicating matters, efforts to spatially and geographically shift computational work to minimise carbon emissions (in effect, aligning compute with solar energy peaks) can inversely increase water usage from cooling (Li et al., 2024). Optimising for one environmental outcome can thus come at the cost of another. Making measurements into targets, as researchers in diverse fields have proven, often renders those targets ineffective as governance measures, and vice versa (Archer, 2024; Strathern, 1997).

It's also the case that a fair competition in a privileged track for environmental performance may not be guaranteed. For one, the ease of achieving green benchmark performances will vary across the planet, given the unequal geographic distribution of green(er) energy infrastructures and the price premiums of working with best-in-class data centres. Absent a common standard, moreover, there is an incentive for researchers who do choose to report their carbon footprint to select the most favourable means of determining this figure, or to merely report on the best of many runs of a model (Schwartz et al., 2019: 62). An honest competition is not guaranteed and, as other scientific fields remind, the replication of results – even by the same research team – can be an enduring challenge (Baker, 2016). Machine learning research, with its substantially sized training datasets, code bases, and variable factors impacting model training, may raise the gambit of the challenge considerably (Desai et al., 2025).

A final, and perhaps more interminable, complication lies in the vexed relation between information and action. Despite growing awareness around green computing principles, a large gap between ideals and practice still characterises the machine learning field today (Nazaré et al., 2023). The virtuous cycle has yet to take off: the publication of carbon footprints is not presently a widely adopted norm, nor have energy-reduced model tracks revolutionised publishing incentives within or beyond machine learning conferences. This dynamic is not specific to high-performance computing research; the degree to which awareness compels, or is even terribly correlated to, behavioural changes is frequently overestimated (Moser, 2015). Yet, as an additive and voluntary metric, it is fair to say that environmental

considerations still lack the social and institutional pull of other modes of evaluating success. At least for now, the wider research community continues to value (and socially recognise) accuracy and speed more highly than sustainability.

Critique from the margins

While these three prior approaches to developing a green epistemic virtue for machine learning come from scholars working in the field's core, there are also additional perspectives at the margins, looking in. A growing body of critical scholars, digital artists, and computing practitioners are questioning dominant directions and articulating a radical alternative: an ethos not of efficacy, net positive impacts, or peer competition, but of degrowth: of subordinating the design and function of digital systems to external ecological limits.[8] In so doing, this group forwards directions and alternatives that are otherwise unthinkable within the mainstream of resource-intensive computing. They generally do not offer complete solutions for researchers seeking to green their extant research programs, but rather aim to question whether or not such dominant directions are inevitable, desirable, or justifiable. This research proceeds through a range of methods, including speculative design, design fiction, and multispecies design (de Winkel et al., 2020; Nilsson et al., 2024; Santos et al., 2021; Soden et al., 2022; Tanenbaum et al., 2016), testing what is technically possible and exploring what is socially emergent from drastically different computing arrangements. While dialog between this group and those we explored previously is currently minimal, we highlight them here as a useful foil, looking to the margins in order to bring the omissions and common-sense perspectives of the dominant sustainability conversations within high-performance computing into sharper relief.

Participants in discussions about degrowth computing come from a diverse set of research contexts. This includes subdisciplinary considerations (human-computer interaction, media and information studies, and integrated design are especially common) as well as sites for research exchange. Two conferences in particular – the Workshop on Computing within Limits (LIMITS) and Information and Computing Technology for Sustainability (ICT4S) – are important sites for this discussion. Across a plurality of approaches, this community articulates a politics of ecological limits for the future of computing in a warming world, marking a break from other approaches to 'green ICT' (Nardi et al., 2018). Rather than struggling to engineer a way around environmental constraints or otherwise justify the sector's impacts, these thinkers start from the assumption that research agendas and social expectations for digital systems – especially those associated with machine learning – should be oriented towards a future that will have stricter environmental restrictions.

This has significant implications for the 'cornucopian model of computing' that characterises contemporary digital systems (Abbing, 2021). Instead of creating network, storage, and processing capacities that are overbuilt so as to be available in all circumstances, regardless of resource costs, degrowth computing proponents strive to prototype, imagine, and analyse infrastructures of computational sufficiency – contexts where bandwidth and server demand has plateaued, energy inputs are largely intermittent and renewable, and equipment is maintained and recycled over much longer time periods across decentralised networks that more equitably serve a larger global community of users with heterogeneous hardware and bandwidth capacities.

Two case studies exemplify the characteristics of ecological limits for compute infrastructures and the technical and social analyses that follow. The first is Solar Protocol, a network of small, raspberrypi servers, hosted by an international group of stewards and powered by local, off-grid solar energy. Developed by Tega Brain, Benedetta Piantella, and Alex Nathanson, these servers are connected as a shared digital art web platform through a custom networking protocol that delivers content to an Internet audience based on whichever server currently has the highest battery charge (and thus is located in the sunniest location on the planet at the given time) (Piantella et al., 2020). This differs significantly from both mainstream internet protocols, which route content from globally distributed cloud servers based on network speed, and the dynamic carbon-responsive compute distribution algorithms proposed by mainstream researchers and industry, which

seek to factor energy prices, carbon budgets, and latency concerns into the flexible scheduling of large data processing tasks (Bian et al., 2024; Ren et al., 2012). Against the impulse to design additional layers of algorithmic complexity in pursuit of energy efficiency, Solar Protocol instead subordinates the routing and performance of its system to the availability of the sun. Servers either are, or are not, online. They either do, or do not, have the highest battery charge in the network. The sun, accordingly, picks the server. Planetarily distributed computing, in the form of a necessarily global volunteer network, makes this dynamic relay possible. The infrastructure, rather than the infrastructure's users, enact the moral argument.

Solar Protocol's developers provocatively describe this approach as one that follows the "natural intelligence" of environmental systems, in contradistinction to "artificial intelligence," and speak to the virtues of contouring human behaviour and system design around its "logics" (Brain et al., 2022: 5). For the platform, this means designing with intermittence and energy-constraints in mind: server-side static site generation with fairly low-resolution graphics that can fit on a device that can be powered by a relatively small residential solar panel. As a byproduct, the platform involves no adware, blockchains, or trackers. The developers further note, how "transitioning towards the types of computational systems that renewable energy regimes can support… [can provide] rich opportunities for reimagining and redesigning the ways we want computation to be in our lives" (Brain et al., 2022: 4). The fact that many data-intensive tools are not easily reconciled with the energy and hardware constraints of Solar Protocol is presented as a useful opportunity to shed attachments to environmentally and socially harmful directions in digital practice and research. The sole machine learning project hosted on the platform is also provocatively small: a collection of poems generated from hand-transcribed public domain datasets, generated with a mere 32 KB of RAM, a basic Markov chain algorithm, and a direct drive solar panel circuit (Parrish, 2022). Its size, careful data curation, and energetics are a deliberate refusal of machine learning research's dominant tendencies.

The project's platform logics point to the ways that degrowth computing considerations are more than just eco-technical. In addition to the privacy benefits that the developer team highlights by jettisoning user tracking and dynamic site design, the process of building and maintaining a globally distributed network has also involved navigating complex local entanglements with community infrastructures, care work, and skill asymmetries with the stewards who host the servers (Piantella et al., 2023), as well as shifting institutional partnerships and state restrictions on internet traffic. Absent a for-profit company or government agency to manage the infrastructures of digital research, researchers themselves must do the social work of building and sharing resources across distinct and varied local contexts. As a result, the findings of this interrogative design project have been perhaps equally legal, social, and economic as they have been energetic (Brain et al., 2022: 4). Epistemic virtues, figuratively and infrastructurally, take a village to build and maintain.

Beyond the community-building dimensions in its direct network, Solar Protocol's wider approach is politically prefigurative: by building a system that reflects design constraints and energetic norms that are not yet practiced by dominant society, it seeks to emphasise the generative work of the means of socio-technical organisation, rather than to argue only for a given end. As a design provocation, Solar Protocol has circulated widely in media arts circles and been nominated for, or won, several distinctions. It has also hosted exhibitions on its own platform, hosting artists and writers that are further exploring the role of energy-constrained design. By building community through building an infrastructural commons, it wends technical and social alternatives together in a mutually constitutive way.

The politics of degrowth, however, are about more than just cutting back extraneous consumption; they also explore opportunities for synchronicities and mutualism between sociotechnical systems. This is the focus of our second case study: 'information batteries' that intermittently use excess power from renewable energy generation systems for flexible computational work in ways that enhance the viability of increased wind and

solar generation on wider electrical grids (Switzer & Raghavan, 2021).

Renewable energy production is often characterised by periods of intense surpluses, in excess of what grid demand can support. This energy can be diverted to conventional or novel energy storage systems, such as pumped hydro, thermal, or lithium-ion batteries, which add additional financial and ecological costs to energy systems. Alternatively, it can be wasted. However, Switzer and Raghavan's (2021) exercise in 'speculative execution' involves 'storing' surplus renewable production as information products, engaging predictable compute jobs, typical of many machine learning research tasks, as a flexibly-dispatchable energy load. This is an explicit recognition of the fact that computational work, materially, is electricity – and as such, can be mobilised to address dissonant patterns of planetary and social energetics. The researchers calculate that an information-battery-enabled data centre at 90% efficiency would be commensurate with 150,000 kWh of energy storage (Switzer & Raghavan, 2021: 9), smoothing over moments of mismatched supply and demand and thereby providing additional stability and revenue for suppliers to an increasingly fossil-free energy systems. They thus demonstrate how informational work and infrastructures can be integrated into grid management, to the ultimate benefit of the grid.

Compared to Solar Protocol's prefigurative politics, information batteries may at first appear to be far less radical. Switzer and Raghavan (2021) examine existing data centres as they are currently configured, and largely through the social language of market conditions, pragmatically assessing the theoretical effectiveness of the energy costs, compute times, and caching speeds that would make their intermittent, surplus energy-contingent use economically viable to both users and providers of energy resources. In this proposal, research work and payment systems could be leveraged as a means to reduce the costs of wider energy transitions, without necessarily requiring substantial reforms to energy markets or heavy-compute research trajectories. Information batteries aim more modestly to only mobilise existing infrastructures and to avoid building expensive energy storage projects.

Yet, in so doing, this proposal also implies a shift in the relational roles of machine learning researchers, cloud companies, and the grid. Meaningfully, it places environmental and engineering challenges ahead of the immediate needs and interests of the wider ICT sector, finding ways for some computational research methods to support, rather than only increase, the labour of decarbonising electrical systems. Such a shift extends to the researcher's social position; instead of a customer, entitled to on-demand services and guaranteed run times, they are instead integrated into an infrastructural network that prioritises the grid's temporal concerns above their own. Additionally, while the authors acknowledge that many compute-intensive projects will not easily fit into this use case, it does demonstrate how those that do could be financially rewarded. This could in turn provide a way to recognise forms of more sustainable high-performance computing in more than symbolic terms, helping to address some of the extant inter- and intranational resource inequities within the research field discussed earlier in this paper.

These altered roles, and the wider convergence of energy informatics and energy transitions in research and industry, also point to the ways that many computational researchers are increasingly thinking of themselves in terms of 'energy citizenship' (Kumar et al., 2023). This is underlined by the paper's efforts to encourage researchers and companies to see energy and information as largely interchangeable – in Raghavan's words, "the core concept here is that information has an embodied energy to it" (Simon, 2022). In the information battery approach, citizenship and energy are articulated not through personal consumer austerity, but through community practices that make a researcher's compute tasks into a part of a utility's support systems. It also attunes participating researchers into the temporal and spatial dynamics of wind and sun in specific planetary locations, asking researchers to align their efforts with the extant movement of nonhuman forces instead of capturing those forces and holding them entirely in reserve.

This suggests that knowledge work might have a time and a place in which it is particularly favoured, rather than always being an *a priori* good. Along with Solar Protocol, the information battery approach proposes that the problem of climate change for the field of machine learning requires relational situatedness more than metrics, and a willingness to negotiate trade-offs between scientific goals and environmental ones. Green epistemic virtues, in other words, may depend at times more on the humbleness of the scientist than their technical triumphs.

At the same time, the Solar Protocol and information batteries concepts both demonstrate obstacles and challenges to an ethos of computing within limits. Most notably, these provocations from the margins have failed to travel terribly far into the centre of high-performance computing. Solar Protocol's suggestion that there are forms of computer science that may be simply incompatible with ecologically concordant energy systems is not likely to persuade scholars with years of professional experience and existing research programs that require heavy compute loads. Nor can it effectively compete with industry influence in the agenda-setting of computer science education (Marshall & Grooms, 2022) and in adjudicating questions of prestige and pay in career trajectories (Kirdani-Ryan et al., 2024). Prefigurative technical politics may ultimately be better at inspiring new minor traditions than challenging existing major ones. There are also, in the context of global digital networks, practical limits to how far these self-hosted experiments can go; Solar Protocol's servers still operate through corporate internet service providers and across subsea cables and internet exchange points that are designed to maximise up-time and informational speed through largely fossil fuel grids and backup generators. Interrogative design, in order to still participate in extant sociotechnical systems, cannot interrogate everything at once.

Similarly, the information batteries approach, while a technical provocation to reorganise computational expectations and work rhythms around moments of energetic surplus, ignores some of the complexities in the political economy of the cloud. Some large data centre operators, in pursuit of internal environmental goals, are already starting to distribute and schedule some workloads to align with periods of high-renewable energy production on the grid (Koningstein, 2021) and are experimenting with curtailing loads during periods of extreme energy demand (Mehra & Hasegawa, 2023). However, this pursuit has not reduced the expansion of the data centre industry, with its continued base loads, nor has it become a key practice grid managers utilise to negotiate the economics of renewable energy peaks. It has, instead, strengthened the economic role of some demand response programs in the siting and continuity of data centres; witness the rise of cryptocurrency mining businesses that make money both from drawing grid energy into their servers to generate financial instruments, and that make money (at times, tens of millions of dollars) in demand response programs by turning their servers off when energy is scarce (Sigalos & Smith, 2023). More narrowly, it is also the case that, given the heightened expense and limited working life of the classes of GPUs most favoured in cutting-edge neural net research, model training and inference companies are more economically incentivised to run this class of chips inflexibly, at all possible hours (Lacey et al., 2026). Energy responsive computing practices, in other words, may not necessarily limit the kinds or continuities of aggregate informational work. Actually decarbonising these infrastructures will require a more fundamental challenge to free market principles and the social licence of so-called AI.

This points to the problems of academic ownership and control over compute resources –something that is growing rarer as the scale of processing demands within machine learning rises – as well as the embodied carbon and environmental resources in the proliferating infrastructures of the cloud. If ICT companies are unwilling to pursue information batteries as a business case, who will, and how can this not ultimately result in ever-more landfilled silicon? Elsewhere the information battery concept's authors, along with other LIMITS thinkers, propose the construction of mobile data centres, composed of retired server racks in shipping containers than can be flexibly dispatched to areas of seasonal electrical surplus without contributing further to the embodied emissions of the ever-growing, ever-renewing

data centre industry (Switzer et al., 2021). The challenges of building such a system, according to the authors, are threefold: working with geographically variable power systems, squeezing more computational work out of end-of-life units, and coordinating across multiple scales of carbon measurement. The questions of who will pay for these infrastructures and how they will compete in a buyer's market of hyperscale compute, conversely, remain unaddressed. In Thomas Hughes' (2012) terms, the mass computation consumption problem is a 'reverse salient' where a potentially significant advance is being inhibited along a specific dimension: ICT's otherwise exponential demand for material and energy flows.

Conclusion

Within machine learning, discussions around green epistemic virtues have been defined in reaction to current exponential trends in resource use, and characterised by a range of overlapping social values, technical conditions, and forms of favoured conduct – the interrelations of which are frequently at least partially acknowledged and mobilised by proponents. Researchers at the margins have further expanded the horizons and potential ends of this transition by providing critiques and strategies predicated on degrowth thinking. As these discussions prove, the problem of climate change could come to mean many things to the research community, from proposals to better attend to in-group inequities, to externalise responsibility to parties upstream and downstream of research, to form new measures of competitive excellence, or to subordinate and enmesh the practice of science within dynamic and global energetic infrastructures.

While there yet is no consensus on what a positive definition of sustainable computing might be, there is emerging agreement among (at least a small but growing group of) proponents that some sort of green epistemic virtue should be cultivated. Across these examples, changes to in-group social recognition, along with technical improvements to cloud computing infrastructures, are still the primary means by which such a transformation is imagined to take place. Whether a question of efficiency, net benefits, competitive achievement, or computing within limits, sustainable compute-heavy research is imagined as a direction of travel for the community via many overlapping and noncoercive means, reflecting the importance of social coordination in such a transition. However, these emergent values and strategies have yet to effectively mobilise awareness into large-scale action and ideals into persuasive collective incentives for planetarily-responsive research methods.

While we have examined the barriers and limitations to each intersecting approach, we don't intend to presume that such challenges are totalising or intractable. It remains to be seen what the future progress of these efforts may win, or where unexpected openings in the sociotechnical fabric may occur. Researcher and corporate engagements with the issue may be heightened by continued media attention, personal experiences with climate disasters, or changing expectations and innovative ideas from peers. Institutional pressures, in the form of university sustainability plans, government regulations, or revised research ethics requirements may add further momentum to this cause. Economic fallout from the eventual end of over-hyped large language model tools will doubtlessly provide another. As these debates progress, further scholarship – particularly by ethnographers – will be highly valuable for assessing how administrators, scholars, and technicians in heterogeneous contexts approach the computational and interpersonal challenges ahead through shared deliberations, individual creativity, and the many forms of social coordination that exceed those captured by the print sources we have analysed here.

Finally, regardless of the ultimate efficacy of the varied approaches we analyse when it comes to actually reducing compute-heavy research's environmental impacts, and the epistemic virtues that may be required to these ends, we want to highlight their value as an analytic resource in the study of political deliberations within scientific communities. As recent research shows, climate change is exerting new kinds of pressures on the traditional boundaries drawn around academic freedoms – whether in the individual academic's pursuit of mobility and prestige goods, now cast in newly rivalrous terms (Katz-Rosene & Pasek,

2024; Sheller, 2022), or in different disciplinary and collective responsibilities to self-regulate (Hardy, 2024). As this study demonstrates, many within machine learning communities do not imagine the environmental impacts of their work to be exempt from public or internal scrutiny – explained away as a necessary cost of curiosity-driven research. In fact, these communities' professional and infrastructural entanglements with digital tech sector companies, whether as direct employers or indirect data centre providers, likely intensify these questions, even as these relationships often delimit what is imagined as obvious and actionable in the pursuit of more sustainable futures. What's more, the grounds for future collective action may be particularly good; in a recent survey of natural language processing researchers, a majority agreed that the carbon emissions of model training should be a major concern for the field (Michael et al., 2023). At the same time, only 17% agreed that scaling up machine learning models would likely help address real-world problems, and a further 67% asserted that the majority of work being published in their field was of questionable scientific value (Michael et al., 2023). The meaning of 'good' knowledge and 'green' knowledge are legibly poised to align here. This is, potentially, an eminently organisable group.

One implication of these factors for STS thinkers and environmental advocates engaging on the issue is the need to take stock of the internal analyses happening within the field. The goal cannot simply be to demand that machine learning scientists become ecologically educated, moving from ignorance to action. This work is already proceeding from within. Similarly, despite potential limitations, the proposals in play all exceed mere technosolutionism, and include complex accounts of social relations, both within proximate research institutions and across a wider global academy. It is therefore essential to track how machine learning researchers develop their own internal theories of change, how they increasingly understand social, infrastructural, methodological, and planetary outcomes to be mutually entangled, and how they seek to expand or limit moral and material imaginaries that might better respond to such a conjuncture. This knowledge can provide further points of leverage. For one, and breaking from previous periods of epistemic virtue formation that were predicated on the formation of new scientific selves (Daston & Galison, 2007), the texts analysed in this article suggest that this community is taking the group, rather than the individual, as the central agent in this political story. External advocates, seeking to engage researchers, might do well to do the same.

Finally, these discussions point to the increased importance of method in struggles over the internal composition of the research community as well as the wider worlds it helps enact. Methods, as John Law (2004) argues, are constitutive. They help make the worlds they describe. Global warming ups this ante. How machine learning knowledge is valued and sought – especially when formalised in shared methods and standards of inquiry – has at least three kinds of constitutive impacts: it shapes both the technical futures it brings into being, the social and demographic character of research communities, and the ways that heavy-compute inquiries themselves act on the energy and climate systems, warming the planet bit by digital bit. A high-carbon future for these fields is likely to be one with worsening distributional injustices in both the differential global opportunities to create new knowledge and in the negative impacts of climate change. Lower-carbon research norms and shifted epistemic virtues, conversely, could provide social, environmental, and creative dividends. A coalitional politics to reform research methods for both climate and equity reasons lies ahead (Pasek, 2026). Perhaps the task for science and technology scholars today lies in determining how best to enter into these budding coalitions and to help them overcome the current impasse.

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Notes

1 In this article (and elsewhere) we somewhat stubbornly distance ourselves from the AI moniker in an effort to more accurately describe and demystify the computational work and infrastructures of this field. Descriptions of 'intelligence' work against this goal. For more on the long history of such rhetorical lines in the sand, see Loeb (2021).

2 This figure (somewhat unusually) includes water use in electricity generation, not just use in data centres specifically. Some have argued that this leads to unfair comparisons.

3 We thank Dawn Nafus for this point.

4 This is to say, researchers can potentially 'buy' results (and thus a publication) by simply purchasing additional compute and/or data to feed into a model to produce an advance, rather than exploring novel approaches or testing hypotheses.

5 Cryptocurrency makes for a particularly easy villain even though, from an infrastructural perspective, Bitcoin mining and neural net training are not so dissimilar. See Cooper (2023) for a further discussion on this point.

6 Some researchers, aided by reporting metrics from their cloud providers, may also choose to purchase further carbon offsets. See Qin et al. (2022) for an example.

7 This is, of course, a fairly large presumption about the ease of research collaborations across North/South divides, and the harmful effects of power asymmetries that arise therein.

8 It is difficult to assess the total size of this group using our social cartography approach. However, it's fair to assume that degrowth proponents are considerably smaller than those of the more mainstream approaches to sustainability previously covered in the paper. For example, the 2024 LIMITS conference featured only 11 papers. ACM FAccT (The Association for Computing Machinery Conference on Fairness, Accountability, and Transparency), conversely, is a conference associated more directly with a reformist, ethical AI framework, inclusive of environmental efficiency measures. Its 2024 conference included over 175 papers. Though they do not all concern environmental questions, they represent a larger audience for that kind of conversation.

From Cloud to Fog: Exploring the Rhetorical Visions and Sociotechnical Entanglements of Corporate Data Centres and Artificial Intelligence

Mads Dahl Gjefsen
NTNU Social Research, mads.gjefsen@samforsk.no

Synne Svinsås Gjønnes
Department of Social Anthropology, NTNU

Benjamin Sovacool
Department of Earth & Environment, Boston University

Can Hankendi
Department of Electrical and Computer Engineering, Boston University

Ayse Coskun
Department of Electrical and Computer Engineering, Boston University

Anna-Laila Danielsen
NTNU Social Research

Abstract

Global tech corporations are recalibrating their sustainability ambitions as they grapple with the surging projections of digital infrastructure's energy and resource needs associated with generative artificial intelligence. Against this backdrop, this article seeks to develop constructive cross-fertilisation between STS and scholarship in de-/post growth by exploring changing parameters for digital sustainability discourses. We document eight 'rhetorical visions' by which Big Tech and other tech actors rhetorically reconcile digital and economic growth trajectories with sustainability. Together these visions ostensibly render sustainability both legible, measurable, and attainable, but they increasingly also precondition sustainability on continued expansion of digital infrastructure and products. Accordingly, to the extent that data centres are a focus point for making sustainability visible, we may say that yesterday's 'clouds' are giving way to a kind of 'fog': elusive yet grounded and palpable in the literal sense, while offering veiled and fuzzy legibility of digital extractivism in the metaphorical one.

Keywords: Data Centres, Extractivism, Growth, Rhetorical Visions, Promissory Narratives, Visibility

Introduction

Attention to the socio-ecological implications of data infrastructures appears to be rising in multiple global domains, including in popular media, civic mobilisation, and policy and regulatory arenas (Edwards et al., 2024; European Commission, 2023; Osaka, 2023; Taffel, 2023). This tendency became increasingly evident during the first half of the 2020s, not least after OpenAI's release of ChatGPT in 2022 prompted both "trillions of dollars of market capitalisation" and "growing concerns about skyrocketing electricity demand" (IEA, 2025: 13; see also Kindig, 2024; JLL, 2024). On the one hand, such developments are indicative of an ongoing process of what we might call

'declouding,' wherein popular conceptions of the cloud as intangible are increasingly giving way to views of the digital as planetarily grounded. On the other hand, however, even these tendencies towards clarity and transparency nevertheless tend to perpetuate analytical separations between data infrastructures and the commercial forces that build and control them.

Here, 'Big Tech[1]' and other data centre actors represent an unparallelled concentration of capital and socio-political influence (Khanal et al., 2025; Leclercq-Vandelannoitte & Bertin, 2024; Birch & Bronson, 2022). These actors also stand as the primary sources of available information and active targets of on-going efforts to render the planetary grounding of data infrastructure more transparent in governance terms (Hankendi et al., 2025). Against this backdrop, we in this article set out to marshal analytical resources from STS, to confront the tendency of analytically separating data infrastructures from the corporations that run them. Our specific object of study is corporate actors' 'rhetorical visions' (Sovacool & Ramana, 2015) of how data infrastructures might underpin, in knowable and transparent ways, digital sustainability in the face of continued digital growth and accumulation.

One motivation behind this approach is the desire to promote increased cross-fertilisation between STS and scholarship in degrowth and post-growth (Hickel & Kallis, 2020; Kallis, 2011). Despite their shared interests in sociotechnical change and notions of development and progress, engagement across these fields is still nascent (Sharma et al., 2025). The former camp has recently criticised the latter for engaging with infrastructures as predominantly technical domains "devoid of political and ideological mechanisms" (Pansera et al., 2024: 2), and for tending to overlook seeds of change in public reasoning around technological innovation that depart from past governing rationalities fixated on growth (Frahm & Doezema, 2025: 322). We contribute to these debates by showing how productive exchange can happen around the topic of rhetorical visions, where STS (supported by methodological resources from discourse analysis) offers complementary analytical strategies to those of degrowth and post-growth. This analytical combination is particularly useful in situations where technologies are assessed (and contested) with reference to energy and climate implications. Such a focus also broadens our understanding of how digital infrastructures and the expectations associated with them become passage points between planetary matter and knowledge practices, contributing to the goals of this special issue.

Data centres are the central feature of our object of study; they depend on vast amounts of a range of planetary inputs, including energy and rare earth materials, thus contributing to environmental degradation (Crawford, 2021; Dwivedi et al., 2022; Rella, 2023), disproportionally affecting the global south (Valdivia, 2024). Research into these issues is both largely quantitative and methodologically challenging. In a recent contribution to degrowth debates, Pasek et al. (2023) showed how analyses of computing's climate impacts and decoupling potential are marred by practically irresolvable methodological inconsistencies around global carbon footprint estimations (c.f. Andrae & Edler, 2015; Malmodin & Lundén, 2018). Their proposed alternative takes the form of relational footprinting (Star, 1999) within valid and restricted system boundaries, so that resource-efficient configurations may be favoured over geopolitically determined clusters and patterns of concentration (Pasek et al., 2023; see also Roussilhe et al., 2023; Masanet et al., 2020; Hintemann and Hinterholzer, 2019). But this prescription remains somewhat mechanical in scope, insofar as it avoids engaging with the intricate infrastructural politics that would be implicit in any global-scale rationalistic rearrangement of computing infrastructures.

Big Tech are major players in these politics, standing as potential enablers of techno-solutionist agendas (Cowls et al., 2023), but simultaneously also challenging the very foundational categories of traditional political theories of power through their sheer scale and the extent to which their platforms are interwoven with our social fabrics (Khanal et al., 2025; Leclercq-Vandelannoitte & Bertin, 2024; Birch & Bronson, 2022). In these respects, the 'industrialisation' of AI (van der Vlist et al., 2024) and monopolisation of Big Tech runs counter to digitalisation's potential to support deep sustainability (Lange et al., 2022;

Luitse, 2024; Randerath, 2024), for instance by undermining democratic accountability and exacerbating socio-economic inequalities (Jones, 2023; de Freitas Netto et al., 2020; Montgomery et al., 2024; Temple, 2024; Gregg & Strengers, 2024; Zuboff, 2019).

Accordingly, data centres cannot be reduced to objects of contestation at local or individual scales (Johnson, 2019; Upham et al., 2023; Gjefsen & Johansen, 2023; Edwards et al., 2024) but are intimately tied up with data centre actors' roles in issues of geopolitics under headings such as industrial policy and security. A richer understanding of how these actors contribute to forms of technological legibility and transparency, and the role of growth dynamics in these processes, thus constitute important areas where STS could inform interpretations of 'growth dependencies' and imperatives that current degrowth scholarship seeks to make quantitatively visible (Janischewski et al., 2024; Keyßer et al., 2024). Additionally, these contributions would also help to carve out spaces for associated normative movements towards 'digital sufficiency' (Santarius et al., 2023; Jungell-Michelsson & Heikkurinen, 2022; Princen, 2005).

Our starting point is thus that Big Tech and other data centre actors not only do the work of expanding digital infrastructure materially, but that they also do so discursively in ways that influence collective imaginations (Jasanoff & Kim, 2009) about digitalisation and sustainability. This is in keeping with Edwards et al.'s (2024: 13) call to "keep our eye on promises made by Big Tech" in studies of data centres. Recognising that the concept of 'sustainability' is already fraught with debates around its meaning and blind spots (Vogt & Weber, 2019; Ruggerio, 2021), we do not impose any single definition of it here but concentrate rather on how tech actors themselves connect the topic to data centres.

We ask: What roles do data centres and AI play in the evolving discourses around digital sustainability among Big Tech and other tech actors? Empirically, we assess tech actors' portrayals of infrastructure and sustainability (company websites), changes in how connections between these two have been articulated prior to and during the still unfolding surge in attention to AI (sustainability report series), and efforts to anticipate and address criticisms and counterclaims (news and media contributions). Analytically, we draw on the STS tradition for studying discourses as co-constitutive of technologies' 'sub-politics' (De Vries, 2007), via a diverse literature broadly concerned with what we here refer to as promissory narratives, whose analytical approaches include rhetorical visions (Sovacool & Ramana, 2015), but also related notions such as 'sociotechnical imaginaries' (Jasanoff & Kim, 2013) and 'technological fixes' (Markusson et al., 2017). We use Sovacool and Ramana's (2015) framework for studying the functionality of rhetorical visions, and identify and discuss eight such coexisting visions of data centres as: (1) neutralisable via offsetting, (2) planetary control-panels, (3) sustainability enablers, (4) better at scale, (5) accelerating promise while decelerating harm, (6) growth dependent, (7) evidence machines, and (8) transition mechanisms.

We begin by positioning our research approach in relation to current research on data centres and tech actors' sustainability efforts, before outlining our conceptual approach of rhetorical visions and 'sociotechnical entanglements.' We then explain our research design before integrating findings and analyses in two main sections on, firstly, eight rhetorical visions of digitalisation with and for sustainability, including their functionalities and entanglements, and secondly, a discussion of how Big Tech initiatives and efforts render sustainability meaningful and legible via data centres. Our conclusion summarises the main findings, limitations, and implications for future research. Ultimately, our article unpacks how promissory narratives around data centres and AI seek not to build transparency or improve clarity over their environmental or social impacts of the 'cloud' but instead obscure them through a performative 'fog.'

Background: Current priorities and concerns regarding data centres and sustainability

Research into Big Tech's role in sustainability highlights a complex interplay between technological innovation and socio-environmental impacts. Associated discourses centre on how digital tech-

nologies both advance and challenge sustainable practices across various sectors, and the prospects for a so-called 'twin transition' (Fouquet & Hippe, 2022; see also Cowls et al., 2023). These include hopes that data-driven urban management could transform resource use in cities (Ullah et al., 2024; Bibri et al., 2024, Silva et al., 2018). AI is hoped to optimise energy use, manage agricultural resources, and enhance urban infrastructure, while emission reductions and efficiency improvements support progress towards multiple Sustainable Development Goals (Regona et al., 2024). Yet, these hopes are tempered by the substantial energy demands required to train AI models, raising concerns about their overall carbon footprint, and rebound effects (Dwivedi et al., 2022; Vinuesa et al., 2020; Pasek et al., 2020; TWI2050, 2019; Alcott, 2005; Lange et al., 2020).

The above hopes coexist with an on-going expansion of digital infrastructure that has made data centres critical to digital economies. These facilities host thousands of servers, and the number of devices is expected to exponentially increase in upcoming years, due to the surging demand on cloud services and emerging applications. Some projections have data centres consuming as much as 9% of global electricity demand by 2030 (EPRI, 2024). Globally, data centres consume about 600 TWh of energy as of 2024, but may exceed 1,000 TWh by 2026 (IEA, 2024). By 2034, Google's energy use for only AI operations is projected to exceed Google's current data centre total electricity consumption, which is around 30 TWh (Castro, 2024). Sectoral growth thus raises serious challenges with respect to sustainability and global efforts to reduce fossil-fuel reliance.

Data centres differ in size, purpose, and ownership. Enterprise data centres, for instance, are located in and used exclusively by single companies or organisations, affording high levels of security and control (ABI, 2024). Colocation data centres, by contrast, are operated by vendors who provide facilities and infrastructure to businesses and other 'tenants' who are able to access large compute resources without having to build and manage the necessary infrastructure themselves. Finally, Big Tech companies own and operate large scale data centres, which are often referred as 'hyperscale' data centres, typically housing 5000 servers or more in buildings spanning tens of thousands of square feet.

To give a sense for scale of operations, in 2024, it is estimated that there are more than 1000 hyperscale data centres around the world, half of which are owned by Big Tech companies, such as Amazon and Google (Taylor, 2023a). Although hyperscale data centres are fewer in number, they consume a significantly higher total amount of energy compared to other data centre types. To meet the increasing demand, the number of hyperscale data centres is expected to linearly increase in the coming years. For instance, Amazon is planning to spend $150 billion for the next 15 years to meet the demand that is fuelled by recent advancements in AI technology (Day, 2024).

To reduce their carbon footprint, all Big Tech companies and many others in the tech sector have committed to 'headline pledges' such as "net-zero carbon by 2040" (Amazon) "carbon neutrality by 2030" (Apple), and "carbon free and net zero by 2030" (Google) (Day et al., 2022: 5, 54, 56, 76). Such pledges stand front and centre of these companies' sustainability reporting and other official communication. On their face, claims and targets for how much of companies' energy consumption is based on renewable sources, suggest that the cancelling out of negative environmental impacts is within reach, such as by reducing fossil fuel reliance and improving resource efficiency. Yet they do not necessarily differentiate between companies' own activities and ones that are offset via market constructs, and what is more, Google and others have recently begun to fall behind on their stated targets due to the massive expansion of infrastructure being developed to power AI (Horton, 2025).

That data centre operators and service providers are failing to adequately demonstrate the sustainability of their facilities has led some Big Tech firms to call for radical change. Lenovo (2025), for instance, reports that while 90% of those in the industry reported that they expect AI to significantly increase data usage, only 41% are ready to integrate it efficiently, implying that issues of energy consumption, sustainability, and carbon emissions are an afterthought for many. In

response, Lenovo proposed four different futuristic images of a more sustainable data centre future. Figure 1 shows how Lenovo, a global Big Tech firm, visualised these futures, with designs as diverse as 'the floating cloud' where data centres are suspended 30 kilometres above the earth (safely higher than commercial aircraft); the 'data village' where modular data centres are linked to rivers and canals, with a variant of: 'the data spa' using data centre heat to power hot pools; and 'the data centre bunker' which deploys infrastructure underground to avoid overt land use impacts. All of this, to us, expresses a longing back to the metaphorical and discursively unproblematic virtual cloud of old, as a counterreaction to the increasing scrutiny of digital infrastructure's growth trajectories and its socio-environmental implications.

Granted, headline pledges tend to be heavily scrutinised and are often criticised for ambiguity and for exaggerating emission reduction commitments (Bhuiyan, 2025; Day et al., 2022: 5; see also Tripathi & Parihar, 2011; Levite & Kalwani, 2020; Sovacool et al., 2022). Much of this critique targets methodological inconsistencies and accounting practices beyond the tech sector itself, also targeting dominant international standards for corporate climate and sustainability accounting (Mooldijk et al., 2024). For the purpose of this article, it suffices to say that headline pledges and the reported progress towards them depend heavily not just on changes in materially manifest practice and resource usage at individual data centre sites, but the procurement of market constructs and offsetting schemes such as carbon credits, green bonds, and renewable energy credits, which as accounting measures offset certain aspects of data centres' planetary footprints (Mendes, 2023; see also Lohmann, 2005; Watt, 2021; Chiapello & Engels, 2021; Bjørn et al., 2022; Fox, 2023).

Such market-based instruments are themselves *also* consistent targets of critical media reporting (Ray, 2024; Bryce, 2021; Elgin & Rangarajan, 2022), and their usage and centrality to tech actors' sustainability reporting has evolved over time (Bloomberg News, 2022). The tech sector has been a key driver for so-called power purchase agreements (PPAs) with renewable energy developers, a mechanism that the NGO New Climate Institute ranks as having the most transparency and integrity in terms of supporting evidenced initiation of renewable energy production that in principle could reduce reliance on fossil fuels on

Figure 1. Four corporate depictions of sustainable futuristic data centres (Lenovo, 2025, used with permission). The upper left shows the 'floating cloud' design, the upper right the 'data spa', bottom left the 'data centre bunker', bottom right the 'data village'.

the aggregated level of electricity grids (Mooldijk et al., 2024). But these mechanisms, too, remain vulnerable to manipulation (Mooldijk et al., 2024). As the ICT sector continues to expand, PPAs are feared to contribute to a monopolisation of renewable energy by tech sector actors (Mollen et al., 2024). This is already evident in Ireland, where the growth in energy demand from data centres has absorbed all new wind and energy generation between 2017 and 2023, and where further expansions of renewables is posed to continue meeting growing electricity demand rather than displacing fossil fuels (Daly, 2024). Deeper issues concealed by headline pledges, as digital infrastructure scholar Patrick Brodie (2025: 1069) points out, are thus connected with the "infrastructural *growth* associated with data-driven technologies when tethered to unequal systems of capital accumulation and its necessarily extractive networks, whether multinational data centres or the similarly private energy systems that they are increasingly shaping and depending on". In this article, we draw on theoretical work in STS to probe the rhetorical aspects of these developments.

Conceptual approach: Promissory narratives/rhetorical visions and sociotechnical entanglements

In seeking to move beyond the common metrics and conventional discourses for data centre sustainability (a staple focus of growth-critical scholarship) our conceptual approach has a dual emphasis on promissory narratives on one hand and sociotechnical entanglements on the other (utilising approaches from STS).

Promissory narratives/rhetorical visions

Multiple studies have looked at discourses around AI and data centres (Bareis & Katzenbach, 2022; Upham et al., 2023; Johnson, 2019; Van Es et al., 2023; Horn & Felt, 2025). However, the specific role of Big Tech in these remains under-explored, even as these actors increasingly "take over the imaginative power of shaping future society [to the point of absorbing] public institutions' ability to govern these very futures with their rhetoric, technologies and business models" (Mager & Katzenbach, 2021: 223). In response to this, we operate here with two closely related terms, namely promissory narratives (a heuristic device) and rhetorical visions (a specific theory). It is necessary to briefly position our use of these terms in relation to other prevalent ideas within STS, the sociology of expectations, and adjacent social-scientific interpretative fields concerned with science and technology as ingredients in future-making.

Importantly, our usage of the term 'promissory narratives' is intended as a shorthand label for a particular type of technology-related discourse and should not be taken as in itself representing any coherent theory. The type of discourse we are referring to broadly includes what corporate actors engage in via official statements and documentation intended for broad audiences (and which in principle therefore encompasses outright advertisement or lobbyism but extends also to official reporting and grey literature). Without attempting any exhaustive definition or delineation, it suffices for our purpose to say that characteristics of promissory narratives include intentionality, advocacy, partiality, and expectation-setting. Promissory narratives are thus associated with explicit technology advocacy (Gjefsen, 2017); and with solutionist discourses in general such as 'technological fixes' (Markusson et al., 2017; see also McLaren & Markusson, 2020).

Accordingly, the notion of promissory narratives contrasts in important ways with both common analytical terms in STS such as sociotechnical imaginaries, which Jasanoff and Kim (2009: 120) refer to as "collectively imagined forms of social life and social order reflected in the design and fulfilment of nation-specific scientific and/or technological projects", and which tend to be applied at national scales and in cross-country comparative studies. Sociotechnical imaginaries warrant mention here as a particularly generative term in STS regarding the deterministic aspects of future-oriented sociotechnical orders (Sismondo, 2020). For Jasanoff and Kim (2009: 123), sociotechnical imaginaries are both "instrumental and futuristic", embedded in cultural norms and meanings, and serve to separate desirable and feasible futures from undesirable ones, mobilising political will or public resolve by helping to define possible pathways for agency (Callon,

1984). However, sociotechnical imaginaries cover more analytic ground and at higher levels of abstraction than what we set out to do here. Our concern is with discrete organisational actors (here: corporations), seeking to advance comparatively instrumental agendas pertaining to market capitalisation but which nevertheless also require broader societal legitimation than monetary gain alone (for instance by furthering sustainability in some form).

To work with promissory narratives conceptually, we therefore use Sovacool and Ramana's (2015) framework for studying rhetorical visions as elements of collective social realities. Sovacool and Ramana's framework has been selected because it, appropriately for our study, synthesises across a broad set of literatures around technologies, expectations and future-making, including literatures in STS but extending to the sociology of expectations, futures studies, and research on sustainability transitions (Geels & Smit, 2000; Borup et al., 2006; Brown & Michael, 2003; van Lente, 1995; Segal, 2005; Selin, 2007; Jasanoff & Kim, 2009). Moreover, the framework is appropriate for our level of analysis, since it organises key components of individuals or organisational actors' articulation of technological potential, and the proposed alignment of such potential with higher-level collectively shared and contested sociotechnical imaginaries. In that sense, our study of rhetorical visions offers a contribution to understanding certain parts of what studies of sociotechnical imaginaries writ large might construe as nationally inscribed variations on the theme of digitalisation with and for sustainability. It is with that thought in mind that we occasionally refer to the notions of collective imaginations throughout this article, as a way of indicating the broader societal contexts we position our research in relation to, but while avoiding the explicit use of sociotechnical imaginaries as a theoretical construct, which does not directly inform our analysis.

Our operationalisation of Sovacool and Ramana's (2015) framework, rests on two aspects. First, we use their synthesis of the aforementioned broad range of STS and other literatures into the phenomenon of promissory narratives, to characterise these phenomena as being at once *functional*, *utopian*, *contradictory*, and *selective*. This approach aligns with the STS tradition for incorporating discourse analytical approaches to matters of language and power, such as critical discourse analysis (Blommaert & Bulcaen, 2000; Bucchi & Neresini, 2008; Mager & Katzenbach, 2021), into systematic studies of socio-materially co-constitutive processes – digital sector growth and its evolving justifications, in our case. Regarding the above characteristics, functionality refers to the ability of expectation-setting to create lasting obligations, utopianism to how they foreground societal enhancement benefits over risks, contradiction to the maintenance of sufficient ambiguity to enrol support while evading critique, and selectiveness regarding the uniqueness of the future-making pathways in question; "ignoring the paradox of relying on technology to solve problems brought about by earlier forms of technology" (Sovacool & Ramana, 2015: 98–100).

Secondly, our operationalisation further draws on Sovacool and Ramana's (2015) theorising of these phenomenological characteristics in terms of symbolic convergence theory (Bormann et al., 2001), to explain promissory narratives' broader appeal, via three processes, or mechanisms: dramatis personae (envisioned characters and actors and the dramaturgy associated with them), symbolic cues (set phrases and slogans), and rhetorical visions (the shared basis of a rhetorical community) (Sovacool & Ramana, 2015). Rhetorical visions thus construed – as one dramaturgical component to generate appeal within the broader context of technological and promissory narratives – lets us highlight under-studied patterns in the discourses of Big Tech and other tech sector actors.

Sociotechnical entanglements

Our second conceptual device is sociotechnical entanglements, a longstanding focus in relational approaches to infrastructure (Star, 1999), which informs current investigations into global computing infrastructures and their societal and planetary anchoring, inclusive of planetary matter (Crawford, 2021). Multiple areas of entanglement have already been mentioned above; they include energy grids, systems, mixes and transitions agendas, along with associated market mechanisms

and constructs, and by extension myriad and contested meanings of sustainability. But even more than that, data centres as infrastructure also enable and stabilise entanglements between major corporations and the almost impossibly broad and indeterminate categories of the 'digital' and its 'publics' writ large. This all indicates a near infinite scope for 'infrastructural inversions' (Bowker & Star, 2000) that might analyse the socio-technical and socio-ecological formations that data centres uphold, if one seeks to follow the call of Edwards et al. (2024) to study data centres by looking beyond the centres themselves. Two strands of on-going social scientific research on data centres in particular, might benefit from this approach.

The first of these strands is temporal and can be exemplified by Velkova's (2023) recent study into the decommissioning of an Equinix data centre which had been operating in a repurposed bunker in Helsinki, Finland. She explored themes of obsolescence and the paradoxically generative and degenerating aspect of infrastructure (Howe et al., 2016; Tilson et al., 2010; Gjefsen & Johansen, 2023) and called for greater attention to processes of disassembly and re-composition, and changing constellations existing through and around data centres (Velkova, 2023: 443–444; see also Velkova & Plantin, 2023). Against the backdrop of such single case studies, the scale of data centres' global growth and entanglements, suggest that studying their life cycles (and associated promissory narratives) in the aggregate, could also make useful inroads to on-going interpretative work concerned with infrastructures end-of-life, maintenance and decay (Jackson, 2014; Denis & Florentin, 2024; Ramakrishnan et al., 2021).

The second strand of inquiry is relational and rooted in long-standing debates about the cumulative 'sustainability impacts' of ICT vis-à-vis its global footprints, and in particular the so-called ICT footprinting debates recently summarised by Pasek et al. (2023), discussed above. They propose a relational approach restricted to well-defined relationships, where climactic and geographical differences combined with the awareness that fibreoptic cables are comparatively unobtrusive (from a carbon footprint point of view), and argue that the global internet could be climactically optimised through a focus on "network shapes, rather than scales" (Pasek et al., 2023: 9). For this strand of research, we point to a need to analytically reconnect the growth in and socio-ecological impacts of data infrastructures as material artefacts, to the social forces including very particular forms of commercial actors and associated dynamics (Khanal et al., 2025; Leclercq-Vandelannoitte & Bertin, 2024; Birch & Bronson, 2022; Crawford, 2021).

Research design

Our goal has been to expand on existing critical research into the tech sector by studying discourses on data infrastructure. While elements such as fibreoptic cables and digital waste could have been equally relevant to examine, we chose to focus on data centres given their centrality to both hopes and contestations of the digitalisation-sustainability relationship with the advent of generative AI. We wanted to study major corporations in the data centre field, but this posed classification challenges since relevant corporations are organised differently (for instance as conglomerates) and may be both operators, providers and customers of data centres; much of companies' contributions to public and policy discourses are also articulated via industry associations. Our solution was to define three broad actor categories while also recognising that significant overlap exists between them. The first category is Data Centre Operators, which are often categorised as Big Tech, where some companies are both cloud operators, providers and customers, like AWS and Azure, while others, like Meta, operate data centres dedicated to internal use by the company. The second category is Data Centre Providers that to a greater degree specialise in offering infrastructural services to third parties. The third category is Data Centre Industry Associations and initiatives that are regional and national in scope and tend to have both Operators and Providers as members or signatories (Table 1).

These entities differ in many ways and have released a wide range of grey literature such as press releases, reports, white papers and policy briefs, as well as report series including financial reports and reports on sustainability, 'CSR' (corporate social responsibility), and 'ESG' (envi-

Table 1. Corporate data centre actors analysed

Operators ('Big Tech')	Providers	Industry Associations
Amazon Web Services	Equinix	Asia-Pacific Data Centre Association
Azure (Microsoft)	Digital Realty	German Datacentre Association
Google Cloud Platform	China Telecom	The Dutch Data Centre Association
Meta	Nippon Telegraph and Telephone	The Norwegian Data Centre Industry
IBM Cloud	China Unicom	Climate Neutral Data Centre Pact
		The Data Centre Coalition (US)

ronmental, social, and governance) aspects. Additional communication formats target broader publics or prospective customers, such as GCP's video tours of selected data centre locations (GCP, 2016), and Azure's visualisation of their global infrastructure in a navigable world map interface (Azure n.d.).

Despite the variation between actors and their communication formats, our concern was with one activity they all engage in: the formulation of promissory narratives about data centres and AI in relation to sustainability. We wanted to study the simultaneously socially conditioned and socially constitutive aspects of discourses (Blommaert & Bulcaen, 2000; Sovacool & Ramana, 2015). We sought to do so via three aspects, namely (a) conceptual linkages between infrastructure and sustainability, (b) changes to these linkages alongside the 2020s' still unfolding surge in attention, investment, and concern about generative AI and its planetary footprints, and (c) the role of anticipating and addressing counterclaims and criticisms.

Given this scope and our qualitative and interpretative ambitions, we aimed for an explorative research design. Because there is a comparative shortage of publicly released documents from industry associations, compared with data from corporations, only a small number of sources were included from those actors after manual searches of each association's website. Overall, our inclusion criteria that allowed us to assemble material relevant to our research goals were as follows.

To understand actors' conceptualisation of the relationship between infrastructure and sustainability, (a) we limited inclusion to those five companies that hosted high-level category websites for each of the three topics of regionality, infrastructure, and sustainability (AWS, Azure, GCP, Equinix, and Meta) at the time of data collection, April-July 2024. In cases where company websites were differentiated by reader region, we opted for European and/or US versions. We also included two industry association reports with dedicated sections on sustainability of sectoral growth, for a total of 16 sources.

To explore how conceptual linkages have changed in the wake of generative AI (b), we wanted to compare older and newer company reports, but discovered that even though annual sustainability reports and similarly titled publications were published by nearly all targeted companies, most such report series had undergone such significant changes in structure and scope over time as to make direct comparisons difficult. Therefore, we restricted inclusion to those five companies where annual report series of consistent structure and scope had been published for at least the last five years (AWS, GCP, Equinix, Digital Realty, and NTT), opting for reports up to ten years old when available. We also included one report series from the Dutch Data Centre Association. The date range of these 12 sources spans from 2017-2024.

Finally, to capture how corporations are addressing criticisms and counter claims (c), we conducted a search for news articles indexed at the industry forum Data Centre Knowledge, which includes original reporting as well as reposted articles from Bloomberg News and other sources. A long list of ~40 articles was generated by searching for '[company] data centre sustainability' and manually screening articles to identify the first five hits that cited named company sources in connection with explicit concerns about industry development prospects. Two coders then independently read and ranked each list entry by degree of analytic relevance to our research objectives to produce a harmonised

short list of 14 news articles. Supplementing this list was a series of 5 short briefs published by the Norwegian Data Centre Industry on data centre myths. The data range of these 19 sources spans from 2016 to 2024. The resulting data set is listed in Appendix A.

A thematic coding protocol was then devised to identify salient themes and examples from each of the above data categories, with particular emphasis on recurring rhetorical visions, as we return to below. Two co-authors carried out thematic coding in parallel with regular meetings to compare interpretations and findings. Word frequency searches were also carried out to illustrate changes in relative emphasis over time.

Although the selection logic has sought to include a wide geographical range, the actors studied are predominantly based in European and US contexts. Although the result of a consistent analytical approach therefore, the resulting empirical basis is far from exhaustive; alternative research avenues are proposed in the conclusion.

Eight rhetorical visions and their sociotechnical entanglements

This section identifies eight sets of combinations of rhetorical visions, characters and actors, and symbolic cues, before discussing their sociotechnical entanglements (Table 2). Importantly, these configurations of elements are not mutually exclusive or discrete but co-exist as a range of stances that actors selectively draw on in different situations to emphasise ways that data centres hold significance for questions about the growth-sustainability relationship.

Neutralisable via offsetting

The first rhetorical vision of data centres portrays them as neutralisable from a climate perspective given the potential for carbon offsets, as exemplified via the high attention placed on targets and indicators pertaining to efficiency improvements and the offsetting of planetary impacts (fossil-based energy, carbon emissions, and greenhouse gas emissions). Both operators and providers rely heavily on this rhetorical vision. While some variation exists, metrics are consistently foregrounded in company language around the merits of their data centres and appear to suggest an effort to zero out the sector's primary ecological impacts using labels such as 'energy-saving data centres' (NTT, 2015: 41), 'water positive' (Amazon, 2024: 41), 'net-zero', and '100% renewable', along with power usage effectiveness (PUE) rates approximating 1.0, all of which contribute to this rhetorical vision. Following our theoretical framework, this rhetorical vision strand is functional through selective remembrance insofar as that which is amenable to offsetting and aggregation takes focus over qualitative aspects such as local community experiences, or area use and biodiversity implications. Moreover, Google's recent decision to stop buying cheap offsets in the wake of forecasts for AI's accelerating resource requirements could indicate limits to how useful or maintainable this rhetorical vision is long term (see also Markusson et al., 2017).

Planetary control panel

The second rhetorical vision depicts data centres as essential components of planetary control panels, and its logic rests upon the cumulative usefulness of big data – organised and made accessible through interfaces for searching, analysis, viewing and tracking socio-environmental concerns to offer "a living, breathing dashboard for the planet" (Google, 2016: 1). The rhetorical vision is accompanied by suites of software solutions such as Google's 'Carbon sense' tools, and it is integral to the continued expansion of digital services and platforms by data centre operators. A functional contradiction or tension can be seen between this rhetorical vision's emphasis on currently available data, and separate visions of emergent, yet-unknown but promising aspects of AI and the infrastructures that enable it (below).

Sustainability enablers

The third rhetorical vision around data centres as sustainability enablers speaks to the indispensability of digital infrastructure for a broader and mutually reinforcing digitalisation-sustainability dynamic, aligned with that of twin transitions (Fouquet & Hippe, 2022). The functional emphasis of the rhetorical vision is to present data centres as obligatory passage points (Callon, 1984) for the sustainability efforts of other societal actors. It

Table 2. Eight distinct corporate rhetorical visions of data centres

Rhetorical visions of data centres as...	Description	Characters and actors	Symbolic cues
Neutralisable via offsetting	Data centres as targets of efficiency and offsetting	Employees as 'tireless optimisers'	'energy-saving', 'Water positive'
Planetary control-panels	Data centres underpin increasingly sophisticated choices	Informed decision-makers, contrasted by poor decisions due to lack of information	'dashboard for the planet'
Sustainability enablers	Data centres as obligatory passage points for sustainability efforts	Public and private actors requiring increased computing capacities to realise sustainability ambitions	"help our suppliers build, measure, and act on ... sustainability", "enable others ... to use AI for both mitigation and adaptation."
Better at scale	Hyperscale data centres are also closest to sustainability	Large market actors outperforming smaller ones	"3.6 times more energy efficient than ... enterprise data centres", "use 50% less energy than typical data centres."
Accelerating promise while decelerating harm	Technological prospects outweighing socio-ecological risks	Operators enabling new possibilities while neutralising harms	"carbon footprint ... growing more slowly than our business", "pushing the boundaries ... in sustainability ... while embracing the growth of AI"
Growth dependent	Data centres enable and require increasing company growth	Company strategists reconcile sustainability and market performance	"opportunities for growth will be found in the issues for which society expects solutions", "business opportunities from climate-related initiatives"
Evidence machines	Data centre use converts to environmental accounting records	Computing customers purchasing evidence of sustainability	'Green Power Reports', "customers can claim renewable energy coverage"
Transition mechanisms	Offsetting mechanisms prompt clean energy development	Data centre operators as transition financiers	"bringing more renewable energy generation sources online"

is most expressed by data centre operators, and exemplified by Google's emphasis on AI for sustainability, to which we return below.

Better at scale

The fourth rhetorical vision depicts data centres as 'better at scale'. This rhetorical vision is especially visible among hyperscale-operators such as Amazon and Google, with less emphasis among providers such as Equinix and Digital Realty. The rhetorical vision centres on the relative advantages of hyperscale facilities and aligns closely with the logic of the efficiency measures underpinning the neutralisable via offsetting rhetorical vision, pitting hyperscale operators against other data centres: "compared with Google, the average data centre uses nearly six times more overhead energy for every unit of IT equipment energy" (Google, 2016: 17).

A degree of tension or contradiction may be visible between this rhetorical vision and that of sustainability enablers above with respect to locating agency, and a question opens up about which societal actors the new and improved sustainability practices of the future should be expected to come from. A selective remembrance can also be discerned in so far as the implication is that sustainability is enhanced via continuously centralised dominating tech actors rather than through some decentralised form. Paradoxically (Gjefsen & Johansen, 2023), the increasing monopolisation is thus in one sense supported by

the evidenced hyper-efficiency of hyperscale data centres, which give legitimacy to claims of having the most sustainable operations.

Accelerating promise while decelerating harm

The fifth rhetorical vision sees data centres as more promising than harmful. Here, the focus is on addressing the trajectories of the sector's planetary impacts vis-à-vis future expectations of projected sustainability benefits, and stressing the contrasting rates of acceleration between the two:

> amidst the growth of our Company driven by AI and other technologies, we recognise our responsibility to lead in sustainable practices and contribute to a healthier planet. … we remain dedicated to pushing the boundaries of what is possible in sustainability and operational performance while embracing the growth of AI and other emerging industries (Digital Realty, 2023: 3).

Functionally, the rhetorical vision claims novelty by depicting (neutralisable via offsetting) data centres as evidence for decoupling: "our carbon footprint has been growing more slowly than our business— proof that economic growth can be decoupled from environmental impact and resource use" (Google, 2016: 3). Moreover, the strands of digital accumulation that lie behind growing ecological footprints of the sector are not differentiated, as the future potential makes it unnecessary to problematise the relative social costs or benefit of different tendencies accelerating digital acceleration. A contradiction can be seen in relative emphasis between the planetary control panel and the more promising than harmful rhetorical vision, with the former resting on currently existing computational potential and the latter resting on yet-uncertain beneficial implications of AI. Both data centre operators and providers employ this rhetorical vision.

Growth dependent

The sixth rhetorical vision portrays data centres as growth dependent, as simultaneously vehicles for and dependent on continued company growth, with reference to societal (market) trends of the increasing urgency of sustainability concerns. The rhetorical vision is employed by data centre operators and by providers. For example, Digital Realty (2018: 3) writes that "We see business opportunities from climate-related initiatives reaching an inflection point … We recognise these trends as transformational business opportunities". NTT (2015: 4), similarly, states that "opportunities for growth will be found in the issues for which society expects solutions. In other words, our business and CSR initiatives cannot be separated, and neither can our Medium-Term Management Strategy and the fulfilment of our social responsibilities".

Evidence machines

A seventh rhetorical vision is of data centres as 'evidence machines'; useful infrastructure whose environmental performance in carrying out computational duties for clients can also generate reports ready-made for customers' environmental reporting purposes. This rhetorical vision is particularly central to the business models of data centre providers. Here, the (neutralisable via offsetting) data centres' performance becomes marketable as a sustainability service in itself, attuned to environmental monitoring regimes, as exemplified via the Green Power Reports marketed by Equinix, which we return to below.

Transition mechanisms

Finally, an eighth rhetorical vision of data centres as transition mechanisms is employed by operators and providers alike. This rhetorical vision is commonly raised in report sections dealing with the purchasing strategies for offsets, where the relative merits of different market mechanisms for offsetting are discussed. Frequently too, it refers to geographical variation and the availability of renewable energy in electricity grids in world regions:

> We believe data centres can leverage their large electricity loads for positive social and environmental impact. Equinix's 100% renewable energy goal is bringing more renewable energy generation sources online both locally and regionally in order to address the urgent need to move utility grids away from fossil fuels to address climate change (Equinix, 2023: 22).

Functionally and selective remembrance is in play insofar as this rhetorical vision rests on a notion of increasing energy needs intimately tied with prospects for company and activity growth, rendering irrelevant questions about reducing usage, intensity, and acceleration.

Entanglements, temporality, integration and discontinuity in corporate sustainability discourse

With the above rhetorical visions in mind, we now turn to the material entanglements of these promissory narratives and discourse, as well as how connections between digitalisation and sustainability (with and via data centres) are shifting, amid the unfolding surge of attention and concern around AI.

Sociotechnical entanglements and temporalities

Although Section 5 focuses on the discursive aspects of eight rhetorical visions rather than the studied companies' quantified environmental performance, there are multiple entanglements implicit in these narratives, that appear increasingly entrenched once one considers the gap between the sector's rising absolute footprints and its performance when market-based offsetting mechanisms are taken into account. The latter of these trends – generally foregrounded in reports – suggests steady progress. Decreases are seen among those who report on carbon intensity, expressed as CO_2 equivalent emissions per USD of gross merchandise sales (Amazon, 2018, 2023), or of revenue (Google, 2016; Equinix, 2015), a trend Amazon's cites as evidence of "how we are working to decouple emissions growth from business growth" (Amazon, 2023: 11). And in terms of renewable energy coverage, there is a marked rise among most companies over the surveyed time period; Google, Amazon, Equinix and Digital Realty all report high increases in their renewable energy ratio (up from 44 to 100% for Google, up from 50 to 100% for Amazon, up from 41 to 96% for Equinix and from 30 to 66% for Digital Realty).

But as was explained earlier in section 2, offsetting mechanisms conceal absolute trends. Absolute numbers for greenhouse gas emissions as well as for energy usage show that the same period has been marked by rapid growth of data centre infrastructure and activity. Table 3 shows a sample of reported greenhouse gas emissions (location-based scope 2 emissions, which includes data centre operations but not compensations attributable to marked-based offsetting mechanisms), illustrating marked growth in both categories between the older and newer reports examined (as is also closely tracked by numerous other industry observers, such as the New Climate Institute). When it comes to energy consumption, Google reports a more than four-fold increase between 2015 and 2023 and admits that as they "further integrate AI into our products, reducing emissions may be challenging due to increasing energy demands from the greater intensity of AI compute, and the emissions associated with the expected increases in our technical infrastructure investment" (Google, 2024: 31). Amazon does not publicise its energy usage but have recently raised concerns by changing its approach to carbon offsetting verification (Furness, 2024). Google meanwhile has also recently abandoned its claim to carbon neutrality via offsets (Rathi, 2024).

What these indicators fail to convey, of course, are the extensive planetary and societal entanglements that are associated with the growth of the data centre sector. These include human activity along associated global material supply chains and extractive practices (Valdivia, 2024;

Table 3. Absolute changes in reported greenhouse gas emissions and energy consumption for Equinix, Digital Realty and Google

	Greenhouse gas emissions (mt CO_2e)		Energy consumption (GWh)	
	From	To	From	To
Equinix (2015 v 2023)	1 122 413	2 610 200	2 600	8 170
Digital Realty (2018 v 2023)	2 770 400	3 451 583	6 448	11 368
Google (2015 v 2023)	2 694 531	9 252 900	5 743	25 307

Crawford, 2021), but also the changing configurations of emerging renewable energy landscapes that are increasingly monopolised by Big Tech (Brodie, 2024). Both are sites of important tensions between the sustainability discourses of tech sector actors (enabled partly by offsetting-based accounting practices), and the human and planetary effects of the sector's growth writ large.

In terms of temporalities (Velkova, 2021), we see that Big Tech's discourses and their evidence for neutralisation grow increasingly entwined with parallel future-oriented efforts in areas such as global and national decarbonisation and renewable energy transitions via financing mechanisms. Growth dependencies emerge laterally, as claimed advancements towards sustainability and its enablement within one sector (tech), becomes part and parcel of the financing of advancement in the form of expansion of another (renewable energy). Thus, the tech sector's sustainability entanglements also extend to the types of issues currently scrutinised as 'green extractivism' (Bruna, 2022) and 'dispossession by decarbonisation' (Sovacool et al., 2021), not least via geopolitical tussles and scrambling for rare earth minerals (Walter et al., 2025; Edwards et al., 2024).

Entwining economic growth prospects with sustainability efforts may be dismissed as an unsurprising genre trait of corporate sustainability reporting. However, the need to scrutinise how this is done becomes acutely necessary when a sector's claim to societal value is so deeply tied to the enablement of sustainability as the tech sector increasingly is; this is where the analytical resources of STS complement those of scholarship in post- and de-growth. Attention in STS to rhetorical visions and entanglements helps show how the legitimacy for an overarching view of what we might venture to call a kind of 'precision sustainability' via computing, draws credible largely from the continued data capture and platform development for economic growth within the sector in ways that echo forms of 'performative lock-in' identified in other STS research on national AI strategies (Bareis & Katzenbach, 2022).

Data centres and sustainability intertwined

Across the surveyed documents, Big Tech and other tech corporations appear to consciously integrate sustainability considerations into portrayals of digital infrastructure, where conceptions of sustainability focus primarily on a handful of environmental impact parameters. All the researched companies acknowledge their significant environmental impact and signal active steps to mitigate it.

Among operators, prominent programs and pledges include Google's offering of tools such as the "Google Cloud Region Picker" to help customers select cloud regions based on carbon footprint, price, and latency (Google, n.d.-b). They claim to be matching "100% of the energy consumed by our global operations with purchases of renewable energy, so every Google Cloud product you use has zero net carbon emissions" (Google, n.d.-a). Google also states that its data centres use 50% less energy than traditional systems, leverages AI to enhance operational efficiency, and offers 'Carbon Sense' tools to help measure and reduce emissions (Google, n.d.-a). Similarly, Microsoft markets itself as having been carbon neutral since 2012, aims to become carbon negative by 2030, and holds forth a long-term commitment to compensate for the company's entire historical carbon emissions record by 2050 (Microsoft Azure, n.d.-a). The company describes its cloud infrastructure as an "incredible opportunity to give back to the communities where we operate," highlighting aspirations for social as well as environmental responsibility (Microsoft Azure n.d.-a). Amazon Web Services (AWS) aims to power operations with 100% renewable energy by 2025 and reach net-zero carbon emissions by 2040, through a combination of renewable energy adoption and operational efficiency (AWS, n.d.). Meta claims to support its operations with 100% renewable energy while also focusing on water conservation and restoration (Meta, n.d.). It features a 'global impact map', detailing energy sources by location (Meta, n.d.).

Among providers, Equinix claims that "energy efficiency and environmental sustainability are a part of everything we do," professing a long-term goal of using 100% clean and renewable energy, and branding itself as "the world's most expansive, secure and sustainable data centre platform" (Equinix, n.d.). And from the industry associations

side, the German Datacentre Association boasts activities to support municipal heat network infrastructure, improve waste heat efficiency, and transitioning to climate-neutral data centres by 2027 (German Datacentre Association, 2023: 11). The Asia-Pacific Data Centre Association, for its part, emphasises data centres as significant buyers of renewable energy, thus driving demand for renewable energy development and influencing the transitioning of global energy mixes (APDCA, 2023: 4).

These examples show how tech actors' implicit scales of sustainability vary and range from global to local. The geographical scope of cloud infrastructure is depicted in broad terms and is often divided into regions that can represent entire countries or large cities. Prominent examples of this are Google's 'Cloud Region Picker', the AWS 'Global Infrastructure Map', and Microsoft Azure's uses of the term 'region' when talking about sustainability at scale (Google, n.d.-b, AWS, n.d., Microsoft Azure, n.d.-a). These tools allow users to visualise data centre locations and select services based on specific metrics, including the option to prioritise a lower carbon footprint. The global scope is however also emphasised by the mention of 'planetary observation,' suggesting a commitment to utilising data for analysing environmental changes on a worldwide scale (Google, n.d.-c).

Overall, then, both operators and providers seem to present their data centre operations through a dual conceptualisation of sustainability. On the one hand, companies *selectively* (Sovacool & Ramana, 2015) relate data centres to sustainability via a set of parameters against which data centres can be measured, emphasising indicators for carbon neutrality, renewable energy, energy efficiency, and water usage. Google, Microsoft, AWS, and Equinix all highlight these categories prominently on their company websites. But, on the other hand, the companies also position sustainability as a marketable service offered through their cloud platforms and infrastructures, enhancing sustainability for other users via measurement, data analysis, and resource management tools. In Sovacool and Ramana's (2015) terms, this connection-making is *functional* in the sense of affixing digital infrastructures to societal needs and simultaneously attracting resources. And although present among both company categories, this aspect is somewhat more pronounced among operators in Big Tech, as exemplified by Google's 'Carbon Sense' and 'cloud picker' tools and the trend among Big Tech companies to develop analytical products that help businesses demonstrate evidence of sustainability progress. Industry-wide initiatives like the Climate Neutral Data Centre Pact also signal collective efforts to self-regulate in anticipation of coming European Union mandates (Sverdlik, 2021).

The source materials also gives some indication of how criticisms and counterclaims are perceived and anticipated by corporations. Media coverage highlights multiple critical concerns regarding the data centre industry, particularly focusing on sustainability and community concerns in response to the AI boom. Confronting these, Microsoft, for instance, emphasises a commitment to enhancing the 'environmentally friendly' aspects of AI rather than slowing its expansion: "We fundamentally believe that the answer is not to slow down the expansion of AI but to speed up the work needed to make it more environmentally friendly" (Bloomberg News, 2024). Anticipation of possible local resistance to data centre construction (Shapiro, 2022), such as in relation to water usage (Butler, 2022) is also evident. AWS, for instance, emphasises the company's vast size as a source of community support, stating, "We believe deeply in using our scale for good and using our resources to strengthen communities where our employees live and work" (Shapiro, 2022). These examples suggest a level of *utopianism* (Sovacool & Ramana, 2015) in corporations' connections between data centres and sustainability. It also appears that countering perceived misconceptions about data centres' physical requirements and their role in energy consumption is a priority for industry actors, as exemplified by the Norwegian data centre industry association's published set of briefs debunking common 'myths', such as ones concerning cryptocurrency mining, energy demands and a lack of local workplace-creation (Norsk Datasenterindustri, n.d.). In summary, data centre actors promote a dual conceptualisation of sustainability as both a feature of their material infrastructure, and as

attainable via cloud services that are pivotal to societal sustainability efforts.

The AI surge and (dis)continuities in data centre-sustainability relations

Turning to changes over time associated with the surge in attention to AI, we find that data centres have been a stable focus of reported energy efficiency and decarbonisation efforts across all actors throughout the studied period, 2015-2024. What is surprising and striking however are the continuities and discontinuities that appear in promissory narratives around data centre sustainability after the uptick of attention around AI and its planetary footprint in later years. Broadly speaking, whereas older reports tend to focus on neutralising and optimising data centres' performance in narrowly defined technical and quantitative terms, newer reports increasingly take a view of digital infrastructure vis-à-vis sustainability as one of long-term enablement via digital expansion, with data centres as necessary passage points. Reports explicitly engage with long-term projections of computing's energy needs, which they admit are high but are generally described as uncertain and ultimately justifiable, both in monetary and planetary terms. Sustainability, here, is seen to manifest via societal users and cloud customers, as new digital platforms, products, and services facilitate increasingly sustainable decisions and actions, thus pitting trajectories towards sustainability as co-dependent on continued digital expansion.

It is the very largest Big Tech companies who appear to be the most capable of crafting elaborate packages and suites of sustainability-enabling services, indicating that the growth trajectory is also one that will further reinforce these actors' dominance in the tech sector. Examples of this are found in introductory chapters from the more recent set of company reports, signed by corporate leaders. For example, Google's Chief Sustainability Officer stresses the urgency of taking advantage of AI's potential, noting that "scaling AI and using it to accelerate climate action is just as crucial as addressing the environmental impact associated with it" (Google, 2024: 3), while Amazon's Chief Sustainability Officer similarly states: "We also see an opportunity to use AI to address sustainability challenges at an unprecedented scale" (Amazon, 2023: 4). Digital Realty's President and CEO writes "we remain dedicated to pushing the boundaries of what is possible in sustainability and operational performance while embracing the growth of AI" (Digital Realty, 2023: 3). Google's latest report also quotes recognisable authority figures on climate change economics and equity as referencing AI's prospects as an: "unparalleled opportunity to transform the narrative in the Global South to sustainable growth and development while meeting their future energy needs" (Damilola Ogunbiyi quoted in Google, 2024: 11) and to "unlock new growth that is sustainable, resilient, and equitable—whilst managing the immense and urgent risks of climate change, biodiversity loss, and pollution" (Nicholas Stern quoted in Google, 2024: 10).

When comparing older and newer reports, word frequency searches show that attention to data centres in companies' sustainability reporting has grown for four of the five companies in the surveyed period, by as much as 150% in the case of Amazon, and with only Digital Realty exhibiting a decline. But interestingly this trend of rising relative emphasis coincides with a shift where data centres have moved from taking front stage in chapter hierarchies of earlier reports to a current situation where content pertaining to data centres have been distributed across report sections. For example, older Google and Amazon reports dedicated entire top-level chapters to data centre-specific topics ('Designing efficient data centres' and 'Sustainability in the cloud', respectively (Google, 2016; Amazon, 2018)). Newer reports, by contrast, distribute data centre information across sub-chapters on 'Carbon', 'Carbon-free energy', 'Waste and circularity' and 'Water' (Amazon, 2023), or on 'Net-zero carbon', 'Water stewardship' and 'Circular economy' (Google, 2024). AI, on the other hand, now figures front and centre of Google's newest report, whose four substantive chapters are 'Introduction', 'AI for sustainability', 'Our products' and 'Our operations' (Google, 2024). Judging by coverage alone, then, data centres and their planetary inputs appear to be getting increasing attention even as this attention is also

diluted and increasingly woven into companies' other scales and classificatory systems.

Both older and newer reports share an emphasis on renewable energy ratios, energy efficiency, water use, and carbon intensity as the most common areas of focus in quantifying and making visible what companies are doing to reign in data centres' ecological impacts. The relative efficiency enabled by the sheer scale of Big Tech's infrastructure underpins compelling arguments in favour of data centralisation and continued market dominance. Such arguments are already evident in older reports, such as Google's claim in 2016 that "a business using Gmail alone can reduce the greenhouse gas (GHG) emissions impact of its email service by up to 98% compared with running email on local servers" (Google, 2016: 55). Similarly, Amazon's older report also draws comparisons to the median US enterprise data centre, stating that:

> AWS's infrastructure is 3.6 times more energy efficient [due to its] efficient server population and much higher server utilisation [moreover, when factoring in] the carbon intensity of consumed electricity and renewable energy purchases […] AWS performs the same task with an 88% lower carbon footprint (451 Research as cited in Amazon, 2018: 59).

In newer reports however, we also see the emergence of new indicators and discourses, including ones dealing with social aspects of sustainability, such as the highlighting of local community considerations around Google's water replenishment initiatives, and Amazon's inclusion of targets and progress towards AI and cloud workforce 'skilling', and the distribution of 'cloud computing credits' in support of global health equity (Amazon, 2023). Echoing the regionalisation of sustainability discourses identified above, we also see an increased differentiation between regions when it comes to reporting on where companies operate using 'clean' energy (Equinix, 2023), with Google's most recent report breaking down their reports for PUE rates, water usage and the rates of 'carbon free energy' across nations and regions (Google, 2024).

Several products and services are portrayed as fostering sustainability via the activities of other societal actors, thus commodifying the tech giants' ability to quantify environmental performance on which clients' computing resources depend. Equinix offers ready-made sustainability reporting via its infrastructure and positions itself as:

> The clear partner of choice to help our customers track and achieve their sustainability goals while managing an increasingly complex global power landscape. […] we offer Equinix Green Power Reports (GPRs), whereby customers in our data centres can claim renewable energy coverage and quantify their greenhouse gas emissions based on their footprint. GPRs are calculated based on the Greenhouse Gas (GHG) Protocol and empower customers to track progress against their own sustainability goals and reporting while leveraging our efforts which support the decarbonisation of our customers' supply chains (Equinix, 2023).

Google (2014: 18) states that: "[t]hrough our products, we aim to help individuals, cities, and other partners collectively reduce 1 gigaton of carbon equivalent emissions annually by 2030", while acknowledging that continued digital expansion also means more and bigger data centres:

> In 2023, our total data centre electricity consumption grew 17%, despite maintaining a 100% global renewable energy match. As Google's infrastructure continues to power the digital transition, providing numerous economic benefits across the globe, we expect this trend to continue in the future (Google, 2024: 12).

In response they support 'AI for sustainability' via two efforts: "boldly accelerating climate action with AI" and "responsibly managing the resource consumption of AI" (Google, 2024: 10). Here, the generative, predictive, interventionist and managerial prospects for AI that offers greater insight and control of planetary systems – the areas where Google might continue to expand their platforms and product offerings – are weighed against the responsible management of the accompanying resource consumption, continuing the emphases on infrastructure efficiency and emissions control while also extending these efforts to the realm of 'model optimisation'. Efficiency efforts in infrastructure now extend to the micro level of chip hardware efficiency (Google, 2024: 13; Rella,

2024). NTT, too, describes a strategic reorientation towards market growth accompanied by and integrated with growing production of ever-more efficient infrastructural micro-components (NTT, 2023: 42).

In these ways, AI's incorporation and uptake by the companies is both integral to promissory narratives of continued financial growth, and in harmony with future sustainability, so that such promises remain both *functional*, *utopian*, and *selective* (Sovacool & Ramana, 2015). In this way, our analysis of the corporate actors' promissory narratives, based on Sovacool and Ramana's (2015) framework for rhetorical visions, holds relevance for higher-level studies of collective imaginations as well, including ones focused on sociotechnical imaginaries concerning the relationship between digitalisation and sustainability. There, too, an implicit case for sustainable growth appears to hinge on continued accumulation and centralisation of information-based activity with and via Big Tech actors, in so far as the efficiency of hyperscale data centres relative to smaller ones makes tech giants' solutions ecologically preferable to those of their competitors.

Conclusion and implications for future research

Our study has used the rapid expansion of the global data centre sector in recent years as a context for exploring what roles data centres and AI play in evolving discourses around digital sustainability among Big Tech and other tech actors. We have identified eight rhetorical visions that are employed by different members of the tech sector, while also highlighting variation in when and how these are used and by whom.

Critically, we have shown that promises of sustainability enablement with and via the expansion of digital infrastructure are intensifying alongside (and likely in response to) the recognition that the energy and other planetary inputs to computing are still on accelerating trajectories. Older sustainability reporting and other corporate communication appeared to depict data centres' ecological footprints as in principle curtailable and amenable to neutralisation via measures such as efficiency, optimisation and offsetting. By contrast, more recently accelerating rates of sectoral expansion amid the AI boom appear to have undercut such lines of reasoning and forced a shift towards sustainability promises predicated precisely on continued growth and concentration of computing power. This tendency is most overtly expressed by Big Tech actors, whose sustainability claims increasingly appear to hinge on the prospects for new and improved practices that may be adopted by other societal actors via their emerging platforms and services, so that it is Big Tech actors' hyper-efficient infrastructures in particular that are depicted as an obligatory passage point towards societal sustainability. In the process, the onus of living up to such promises is shifted away from owners and operators of digital infrastructures alone, and increasingly also becomes shared by future prospective customers and users, rendering complicity in the ecological footprints of computing all-pervasive while rhetorically conflating sustainability-promises with other drivers of continued tech sector expansion. That Big Tech retains a central, enabling, and expanding role for themselves thus lies at the very core of the discursive dynamic around data centres.

We have followed the call of Edwards et al. (2024: 12) to use data centres as an entry-point for scrutinising "the modes and modalities by which Big Tech impacts and increasingly shapes society and alters planetary conditions", and in so doing we have aimed to contribute to multiple literatures. Firstly, rhetorical shifts may serve to distract from absolute sectoral growth and an aggregate potential for the kinds of infrastructural unmaking that Velkova (2023) has gestured towards at the individual case level.

Secondly, as a contribution to cross-fertilisation between STS and post- and degrowth scholarship, our study indicates how interpretative studies of rhetorical visions and sociotechnical entanglements from the former can enrich the appreciation for political and ideological mechanisms surrounding infrastructure in the latter (Pansera et al., 2024). This contribution is particularly relevant for the nascent conceptualisations of 'growth dependencies' in post- and degrowth scholarship, which has so far been concerned more with quantifiable relations across societal systems (Janis-

chewski et al., 2024; Keyßer et al., 2024) than with rhetorical and promissory dimensions of growth. Our view is that juxtaposing and integrating studies of growth trajectories with rhetorical shifts around technology, as we have done here, offers a promising way forward for these fields.

Finally, as a contribution to the special issue, our article also provides a basis for cautioning against analytically separating data infrastructures from the commercial forces that operate them in studies of infrastructural mediations of planetary matter. The companies studied here are the primary source of much of the publicly available knowledge about the circulations of energy, water, materials, and people in and around digital infrastructure, but these actors are also both inconsistent and highly restrictive when it comes to sharing operational, emissions and other data (Hankendi et al., 2025; Mooldijk et al., 2024). By examining qualitative aspects of these companies' sustainability reporting over time, our study further enriches the varied research efforts seeking to make sense of the companies' published metrics and official communication.

Our study is not without limitations; our focus on the largest actors in the tech sector has come at the cost of neglecting non-corporate voices and local-level discourses where data centre expansions also play a role in community development discussions, not least outside of Europe and the US. Examining these, and how their regional and global entanglements vary in different parts of the world, constitutes an important focus for further research. Emerging policy and regulatory frameworks, differently developed, justified, and publicly debated in different sites, constitute one promising entry point for such work.

Ultimately, we have documented how data centres and the AI surge provide a focus for Big Tech and other tech actors' efforts at representing sustainability as both legible and attainable via continued digital expansion, even in the face of recently rising projections for AI's future resource needs. Our analysis of rhetorical visions shows how data centres enable corporate actors to reconcile notions of (digital and economic) growth with broader collective imaginations pertaining to digitalisation with and for sustainability, amenable to further study using complementary approaches such as sociotechnical imaginaries. To the extent that we are witnessing a gradual increase in popular awareness and focus on the digital's material underpinnings, we may say that yesterday's 'clouds' are giving way to a kind of 'fog': still elusive, but more grounded and palpable in the literal sense, while offering veiled and fuzzy legibility of digital extractivism in the metaphorical sense.

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Appendix A: Data capture

Entity	Data centre-Sustainability relationship (websites)	Change over time (reports)	Concerns and counter claims (media stories)
Amazon Web Services	*- AWS Global Infrastructure* *- AWS enables sustainability solutions*	*- 2018 Sustainability Report: Thinking Big* *- 2023 Sustainability report*	*- Microsoft's AI Push Imperils Climate Goal as Carbon Emissions Jump 30%* *- AWS Launches Grant Program to Benefit Northern Virginia Communities*
Azure (Microsoft)	*- Azure geographies* *- Azure global infrastructure* *- Azure sustainability*		*- The World's Most Unusual and Unique Data Centres* *- Microsoft's AI Push Imperils Climate Goal as Carbon Emissions Jump 30%* *- Hyperscalers in 2024: Where Next For the World's Biggest Data Centre Operators?*
Google Cloud Platform	*- Cloud locations* *- Google Cloud infrastructure* *- Cloud sustainability*	*- Environmental Report: 2016* *- 2024 Environmental Report*	*- The World's Most Unusual and Unique Data Centres* *- Microsoft's AI Push Imperils Climate Goal as Carbon Emissions Jump 30%* *- Hyperscalers in 2024: Where Next For the World's Biggest Data Centre Operators?*
Equinix	*- Data centres* *- Data centres* *- Green by design*	*- 2015 Corporate Sustainability Report* *- Sustainability Report FY2023*	*- The World's Most Unusual and Unique Data Centres* *- Many IT Leaders Feel Infrastructure, IT Teams Aren't AI-Ready: Report*
Digital Realty		*- 2018 Environmental, Social and Governance Report* *- 2023 ESG Environmental, Social, and Governance Report*	*- Key Data Centre Sustainability Trends in 2022* *- Digital Realty: Trump's Climate Order Won't Change Firm's Clean Energy Goals* *- Amazon Wind Farm to Help Power Iron Mountain's Underground Data Centres*
Nippon Telegraph and Telephone		*- NTT Group Sustainability Report 2015* *- NTT Group Innovating a sustainable future for people and planet: Integrated report 2023*	*- Data Centre Pro Sheds Light on Overcoming Staffing Challenges* *- Preempting Regulation, EU Operators Strike Green Data Centre Pact*
Meta	*- Meta's global data centre fleet* *- Meta data centres* *- Meta sustainability*		*- Is Liquid Cooling Adoption by Data Centres Becoming a Zero-Sum Game?* *- Meta Is Adding Three Data Centres to Already Massive Mesa Campus*
IBM Cloud			*- The Future of Data Centres: An End-to-End Operating System Built on Clean Data* *- Hyperscaler Microsoft - and Peers - Pioneering Hydrogen-Powered Data Centres*
German Datacentre Association	*- Perspectives for a sustainable data centre industry by 2030*		

Entity	Data centre-Sustainability relationship (websites)	Change over time (reports)	Concerns and counter claims (media stories)
Asia-Pacific Data Centre Association	*- How will the Data Centre Industry Support Rapid Digital Growth and Innovation in Asia?*		
The Dutch Data Centre Association (DDA)		*- State of the Dutch Data Centres 2017 - Room for Growth* *- State of the Dutch Data Centres 2023*	
The Norwegian Data Centre Industry			*- Myth 1: Need* *- Myth 2: Jobs* *- Myth 3: Electricity* *- Myth 4: Crypto mining* *- Myth 5: Location*

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Notes

1 'Big Tech' commonly refers to the five dominant tech actors – Alphabet (encompassing Google), Amazon, Apple, Meta (encompassing Facebook) and Microsoft – but we also seek to distinguish these from discourses fronted by other major tech actors that are heavily invested in data centres, such as colocation operators Equinix and Digital Realty, as well as national and regional data centre industry associations whose membership include these and other companies.

Jérôme Denis and David Pontille (2025) The Care of Things: Ethics and Politics of Maintenance. Translated by Andrew Brown. Cambridge: Polity Press. 292 pages. ISBN: 978-1509562381.

Brett Mommersteeg

Humboldt-Universität zu Berlin, mommersb@hu-berlin.de

Nona Schulte-Römer

Technische Universität Dresden, nona.schulte-roemer@tu-dresden.de

The Care of Things is, among many things, a report on the ways in which the world is at risk of falling apart but remains held together within practices of maintenance. It is, broadly, an introduction to the field of 'maintenance studies' through STS sensibilities. In the conclusion, its authors, Jérôme Denis and David Pontille, describe the book as having an "ambulatory approach" (p. 242) that wanders through this field. Along the way, maintenance is told through stories of graffiti removal and metro signs, architectural heritage and vintage cars, artworks and mobile phones, as well as Lenin's corpse and environmental preservation – stories that are sometimes the authors' own, but also often draw from others' empirical research. Throughout the book, STS concepts offer vantage points for readjusting the analytical focus. Material politics and delegation are put to the test by the fragility of things. Attachments appear in relation to a multisensorial attention and vigilance towards objects. As an exercise in 'empirical philosophy' (Mol, 2002), the book thus explores philosophical topics like materialism and objectivity, time and subjectivity, or ethics, responsibility and politics, through situated, empirical studies of maintenance. And all of this is held together in a light, perhaps performative, style of writing that is evocative of the repetitive gestures and refrains of maintenance: a 'narrative matrix' (Despret, 2021) sustained by the voices, practices, and concerns of people who take care of things, observe closely, and hold reality together.

The book, as the authors stress, is partly a response towards what has been referred to as the contemporary 'crisis of sensibility' often associated with the demand to renew our ways of describing, 'becoming-', and 'thinking-with' other modes of existence or beings, like mushrooms, trees, plants, bears, sheep, dogs, or other novel phenomena that have come alive within the ongoing environmental crisis (p. 5; see also Latour, 2015). The authors propose that multispecies sensibilities, however, should not replace the challenge of thinking and imagining our relations with technical things. Maintenance, as a learned practice, form of attention, and 'cultivated art' (Stengers, 2015) draws our attention back towards those once-again 'missing masses' – artefacts, devices, recalcitrant things, and fragile materials – that are equally important components within the fabric of human worlds. Maintenance, they argue, is a way of attending to the world that is also a remediation of this crisis of sensibility. In other words, there are lessons to be learned from the 'art of making things last,' which constitutes interdependent relationships of care and cultivates a

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'material diplomacy' that deals with decay instead of fighting it (p. 57).

An important element of maintenance is that it provides another narrative outside the logics of modernity and its stories of progress, creative genius, heroic actors, innovation, novelties, and discontinuities (Chapter 1). This is also how Denis and Pontille differentiate the more popular notion of repair from maintenance. Repair remains somewhat 'modern', carried out in heroic gestures of fixing things in stories of singular breakdowns, renewal, resilience, and progress (p. 20). Maintenance runs counter to those linear narratives composed of dramatic events. Instead, it is the "practical invention of continuity" (p. 242), the mundane acts of care, tactful adjustments, attentive gestures, or expert techniques that hold something in place, and the often invisible, badly or unpaid work that makes sure that seemingly nothing happens. In this careful 'dance', which requires multisensorial engagement and material choices, a situated ethics of care is cultivated, full of doubt and hesitation (p. 208), relying on a close attention to others' manners of being (Chapter 6). Maintenance therefore affords, as Denis and Pontille stress throughout the book, an emotional or affective sensibility: "maintenance worries about the part of reality that doesn't hold together" (p. 48). It generates a knowledge of the world that is not detached, 'objective', or value-free, but intimate, multisensorial, and attached (Chapter 3). In other words, in maintenance the world coheres in its own specific mode or key. It has, as Étienne Souriau (2015) characterises beings of fiction, a 'solicitudinary' existence. In maintenance, the world is shaded in a particular kind of light, based in concern, care, and 'ontological tact' (Despret, 2021). It begins from the position that the material world is not guaranteed, that things rust, crack, fall apart, and fail, and that there is an inherent 'fragility' of things that requires an attention to how everything relies upon others to exist (Chapter 2).

There are many more maintenance stories and conceptual twists to discover in this book that, en passant, draws together ideas and insights from STS, anthropology, psychology, history of science, and sociology. Of course, they do not miss to problematise time (Chapter 5) and identify four 'ontological gestures' – prolongation, permanence, slowing down and stubbornness – to mark distinct modes of how things come to last. Time also becomes an issue of contestation in conflicts over 'planned obsolescence' and the 'right to repair' (Chapter 7). What is at stake, as Denis and Pontille stress, are the "the most ordinary operations of prolongation" (p. 128) in time, matter, and the interdependent relations with others, human and nonhuman, that compose the world.

Finally, Denis and Pontille sketch out a politics of maintenance that addresses 'material diplomacy', a term coined by the Rotor collective, as a forging of relationships between humans and things. Importantly, this "barely outlined" (p. 7) politics entails the open questions of who and what should play a part in negotiating the terms and conditions of maintenance relationships. At this point, we think the book could offer more of a situated reflection on the limits of maintenance. Instead, the authors give critical hints on how the focus on maintenance might inform critical analyses of contemporary modes of consumption, technological innovation, and the unattained ideal of circular economies. For instance, "[w]hat is commonly called the 'consumer society' is based on a systematic obliteration of the material fragility of things – a denial of wear and tear" (p. 88). Reflecting on their own empirical focus on industrialised countries, Denis and Pontille further admit that the invisibility of maintenance and fragility might be a privilege of the Global North, whereas the (slow) violence of maintenance work is more significant in the Global South. By addressing this harmful dimension of maintenance relationships, the authors just escape the lure of romanticising 'the care of things.'

To conclude, we very much enjoyed this slow and rich book, which cherishes, conceptualises – almost fetishises – the mundane, invisible, and often tedious work of maintenance. The authors have succeeded in elegantly blending empirical stories and theoretical reflection. However, we do see a slightly totalising tendency, whereby everything – even encounters, surprises, singularities, and invention – can become elements of maintenance, and thus wonder: what are the limits to maintenance? These limits must exist, for how else could we make sense of discontinuity and

transformation? In any case, *The Care of Things* can offer STS scholars a highly inspirational account of maintenance and its politics that includes counterpoints to theories of sociotechnical transitions and innovation, translates questions of responsibility and care into infrastructure studies, and provides new perspectives on agency and matter for rethinking our contemporary crisis of sensibility.

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Samuel A Moore (2025) Publishing Beyond the Market: Open Access, Care and the Commons. Ann Arbor: University of Michigan Press. 234 pages. ISBN: 9780472057634.

Aube Richebourg

CNRS Centre de Sociologie de l'Innovation, Mines Paris-PSL, aube.richebourg@minesparis.psl.eu

Who knew that, albeit being two of the most lucrative scientific publishers of our time, Elsevier and Springer Nature are also the leading actors of open access (OA)? In an era where publishers became data companies and hybrid or gold OA a lucrative business model, Samuel Moore's book helps understanding not only the spectrum of OA but also the various logics of governance it entails. Moore convincingly defends one core argument: instead of focusing on OA as a horizon, publishing should be governed with care as a scholarly, small-scale commons.

The core argument of the book is rooted in a critique of OA, yet not as a principle – to which the author obviously subscribes – but as a contemporary social, economic, and political reality. As a principle, OA according to Moore "does not have a fixed meaning or stable politics" (p. 6), which explains the debates over three decades around the distinction between 'green' (based in institutional repositories), 'gold' (based on existing journals and the APC system), and most recently 'diamond' versions of OA alongside their features (infrastructures, costs, availability). As a reality, though, and although it has been invested in by many scholars to reclaim control over knowledge production and dissemination, OA has enriched commercial publishers more than it has harmed the massive control they have over scientific publication. The article or book processing charges (A/BPC) system – that is, authors paying through research grants for OA papers for sums fixed by the publisher – for example represents, according to a publishing consultancy, a market value of over $2 billion in 2022 (p. 16).

In this context, Moore's book addresses a crucial and politically loaded question: how should OA be governed? Moore's answer starts with considering OA in another way than that of a goose laying golden eggs for publishers or a novel market tool for policy makers (p. 22), and instead as a common resource and more importantly even as a 'practice of commoning' (p. 25). The emphasis Moore puts on practices entails a critique of a license-centered understanding of the commons, widely spread in publishing, reducing OA to critiques of ownership and what the legal scholar James Boyle coined a 'public domain of resources' (p. 44). This approach obliterates the commoners themselves and their ways of self-organising production and governance (p. 55). Defining this locally produced publishing horizon for scholars as commoners, Moore underlines, entails an emancipatory potential, which is currently speculative as a possibility (p. 57).

The brick on which Moore builds his answer is thus provided by the general framework of 'the commons'. However, in Ernesto Laclau's words, the commons is a 'floating signifier' that can relate to almost everything (p. 9). Moore's ambition then is to define more specifically what commons within academic publishing means beyond the mere 'freely accessible' feature and capitalist standards (p.11). Drawing on theories of care (Tronto, 1993;

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Mol, 2008; Puig de la Bellacasa, 2017), Moore suggests that commons should be evaluated through a renewed epistemic lens placing the importance on "process over outputs, cultures over outcomes" (p. 27). In this perspective, the lens of care provides an open-ended epistemic framework to assess non-normative relations between humans and objects, and between scholars themselves, and the infrastructures of their careers. Away from simply advocating for more care in scholar publications, Moore subtly uses this framework to support another argument of his book: denouncing the looming homogeneity in marketised publications and promoting bibliodiversity through a variety of small-scale communities. In this sense, the book contributes to the understanding of the threats of commodification of research on its very quality.

Moore's 'entanglement' in the transition to OA, especially his involvement in the Radical Open Access Collective (ROAC), provides him both with epistemic reflexivity and the material to analyse the diverse practices of OA. The epistemic standpoint of Moore, expressed through Donna Haraway's 'staying with the trouble' approach, is that of a researcher involved in "radical open access" politics (p. 30). Being entangled in a dense network of collective initiatives clearly informs the author's perspective: many of the book's arguments are grounded in a collective, cumulative reflection, as evidenced by the many citations to like-minded scholars (e.g. Janneke Adema, Martin Eve, Rebekka Kiesewetter, Cameron Neylon). As for the research materials used by Moore, there are a mix of scientific, institutional, activist, and communication materials and interviews conducted in the research project "Changing Publishing Ecologies. A Landscape Study of New University Presses and Academic-led Publishing" (p. 106). Although the methodology used by Moore is not explicit, one could argue that Moore used what Robert Merton would have called 'strategic research material' for the study of the many entanglements of OA, commons, and care. Those multiple strategic research sites cover different scales and spaces for observing the politics of OA: the institutional level with coAlitionS, the organisational level with Elsevier's Digital Commons or the Creative Commons organisation, and the community level with ROAC. The polarisation of actors involved in OA politics, starting with the institutional and top-down organisations to end with the scholar-led projects, is of great importance for the proceedings of the demonstration. While dominating actors of OA according to Moore "rehearse the values of neoliberalism and are ultimately impotent against the marketisation of publishing" (p. 34), small-scale, scholarly/librarian-led publishers and their infrastructures succeed more in injecting care ethics into OA practices. In other terms: the author advocates for turning away from 'bold' institutional policies like PlanS, condemning the absurd 'commons washing' by for-profit scientific publishers, to invest more into community-based projects such as ROAC.

For STS, Moore's book contributes to the advancement of research on the material and symbolic conditions of academic autonomy. Indeed, investigating academic publishing infrastructures in a context where for-profit companies put publication 'under pressure' (Hanson et al. 2024) appears as crucial as academic careers (Merton, 1942) or science as an autonomous field (Bourdieu, 1976). Another contribution of Moore's book, though not explicit, is to the research on maintenance and the 'care of things' which political reach lies in going against the tendency

of producing always more (Denis & Pontille, 2025). As a community, researchers reading this provocative book are bound to be prompted on the following question: what do we care for? And how to maintain the value of our work? The resistance implied by committing to practices of care instead of the 'choice logics' of for-profit publishers (focusing on individual outcomes, homogenising tendencies of publishing) appears as a new criterium for better science. Finally, a set of critical questions remain fully open, to be further investigated in the future: what are the social conditions of care when academic careers and communities became so fragile? How to invest in academic commons when academics change positions, sometimes even countries, regularly? When is the internationalisation and digitalisation of scientific cooperation not enough to guarantee those conditions? How could institutions foster better practices beyond mere declarative stances?

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