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The world wide web of carbon: Toward a relational footprinting of information and communications technology's climate impacts

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Abstract

The climate impacts of the information and communications technology sector—and Big Data especially—is a topic of growing public and industry concern, though attempts to quantify its carbon footprint have produced contradictory results. Some studies argue that information and communications technology's global carbon footprint is set to rise dramatically in the coming years, requiring urgent regulation and sectoral degrowth. Others argue that information and communications technology's growth is largely decoupled from its carbon emissions, and so provides valuable climate solutions and a model for other industries. This article assesses these debates, arguing that, due to data frictions and incommensurate study designs, the question is likely to remain irresolvable at the global scale. We present six methodological factors that drive this impasse: fraught access to industry data, bottom-up vs. top-down assessments, system boundaries, geographic averaging, functional units, and energy efficiencies. In response, we propose an alternative approach that reframes the question in spatial and situated terms: A relational footprinting that demarcates particular relationships between elements—geographic, technical, and social—within broader information and communications technology infrastructures. Illustrating this model with one of the global Internet's most overlooked components—subsea telecommunication cables—we propose that information and communications technology futures would be best charted not only in terms of quantified total energy use, but in specifying the geographical and technical parts of the network that are the least carbon-intensive, and which can therefore provide opportunities for both carbon reductions and a renewed infrastructural politics. In parallel to the politics of (de)growth, we must also consider different network forms.

Keywords

Information and communications technology, infrastructure, networks, carbon footprinting, energy

Introduction

The carbon footprints of the Internet and the wider information and communications technology (ICT) sector are growing sites of public concern. Whether through the "tsunami of data" predicted to consume 20% of global energy supplies by 2025 (Vidal, 2017) or viral videos with emissions seemingly on par with small nation states (Varghese, 2020), the climate impacts of digital networks have entered public discussion through a range of alarming figures. Whereas in previous years, scholars exerted considerable effort to rebut the supposed immateriality of the sector (Gabrys, 2011; Maxwell and Miller, 2012), a challenge now lies in assessing and responding to the quantification of digital networks' environmental impacts. What should we make of these sectoral numbers, and in what ways should they be mobilized politically?

Responses to these questions have, so far, fit into two main groups. Some quantitative research offers an alarming vision of ever-expanding energy demand in a world still largely lacking renewable capacity, requiring urgent and drastic changes to digital networks and digital culture

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predicated on a politics of global degrowth. In this view, current trends are so threatening to the climate that they demand a fundamental rethinking of the sector's business models and legal liberties. Such unprecedented degrowth is imagined to take shape through a multiscalar advance of consumer actions, regulatory pressures, and public debates about the social value of different forms of digital content (Ferreboeuf, 2019). It poses a vision of the future where Internet use is fundamentally changed: no longer perpetually advancing in streaming speeds, file sizes, and storage, but mostly plateaued if not retreated in scale, especially for uses deemed socially irrelevant (such as pornography, video games, or ultra-high definition streaming video (Efoui-Hess, 2019; Makonin et al., 2022)).

On the other side of the divide, researchers argue that this crisis is overstated. Citing a combination of past and future technological efficiencies, the environmental and social benefits of increased ICT access, and studies that point to the seeming decoupling of emissions from sectoral growth, these scholars and advocates argue that the impacts of digital systems are a net social and environmental good and, at most, an engineering problem that can be remedied by a combination of renewable energy build out and design solutions (Accenture Strategy, 2015; Cunliff, 2020). This presents a vision for the future where the sector continues to grow prodigiously, connecting ever more devices and data sources to a carbon-neutral cloud.

These findings are contradictory and divisive; both cannot be true at the same time, and both present radically different futures for digital culture, capitalism, and innovation. Nevertheless, they share a common scope and logic: on the basis of its global footprint, ICT must be curtailed or expanded.

This article does not resolve this debate. Instead, we argue that the question has been, to a subtle but important degree, wrongly posed. By analyzing the methodological roots of the impasse that has characterized footprinting studies over the past decade we explain how the quantitative study of ICT's climate impacts continues to resist resolution because of perpetual data frictions and disparate study designs. As a result, an impasse between degrowth and decoupling approaches can be expected to continue as long as the question is globally—and thus generically—posed.

Footprinting methodologies are a key site in which politics are practiced. While critical environmental scholarship has examined the effects of carbon footprinting practices on questions of personal governance and social licensing in the general (Paterson and Stripple, 2010; Turner, 2014), we show how research designs themselves complicate larger debates about policy and behavior, even prior to the public circulation of findings. By assessing over 60 published sources in the past 10 years of this debate (including scientific papers, gray literature, corporate publications, and public comments by researchers) we explore how efforts to quantify immensely complex and globally distributed industries can fracture attempts at political articulation.

The ICT sector is a particularly interesting industry in which to weigh such questions, given its considerable scale, transnational networks, and sheer infrastructural breadth. It crosses national, geographic, and sectoral boundaries and is more obscurely monitored than most other economic sectors, creating roadblocks to easy regulation or assessment. In this article, we pay particular attention to the spatial nature of these networks, focusing on how regional boundaries, scalar effects, and the geographies of the energy transition are key and underexplored factors in the acquisition and analysis of data. Spatial relations and differences are missing, and essential, analytics within this wider debate.

To this end, we pose a new approach: challenging the aspiration for a universal accounting, we argue that a different politics of environmental assessment is possible: instead of assessing the carbon emissions of the entire network, what we call *relational footprinting* proceeds from more geographically-grounded and partial perspectives of network nodes. We illustrate the potential payoffs of this approach using one of the global Internet's most overlooked components and also one where the application of such an approach might be more easily facilitated and assessed: the subsea telecommunication cables that support almost all transoceanic Internet traffic. Despite their central importance, they are one of global ICT's least energy-intensive parts and, as a result, have been largely ignored in existing footprinting studies. Drawing on feminist science studies and infrastructure studies (Berlant, 2016; Haraway, 1991; Parks and Starosielski, 2015), we show how attention to relations illuminates new modes of infrastructural connection and in turn opens new avenues for environmental coalitions, politics, and action. In deconstructing the binary of global decoupling vs. degrowth we offer a third option: the reorganization of global infrastructures in order to leverage regional energy differences. In other words, we suggest that the constellation of data centers, cables, and internet exchanges that comprise internet infrastructure could be configured differently across global geographies in order to better mitigate the sector's climate impacts.

We seek to intervene in several key debates. To digital media scholars engaged in the field's infrastructural turn—and the environmental politics it poses—we aim to complicate the epistemological foundations through which we approach our objects of study. As we demonstrate, environmental politics here are very much plural, containing unresolved contradictions and leading toward incompatible social and technical ends. For those engaged more directly in ICT climate policy, we offer an assessment of the key methodological and sociological factors at the root of this accounting impasse, as well as a way to negotiate new paths forward. To both audiences we offer an alternative to rigid commitments to global degrowth or decoupling, suggesting that generative and pragmatic environmental possibilities are legible through a spatially differentiated and technically disaggregated approach to network infrastructures.

Our article starts with a survey and analysis of ICT carbon footprint studies, focusing specifically on common limitations and departures in research designs as well as the wider political debates into which they lead. These include industry control over private data, trade-offs between top-down and bottom-up models of global networks, difficulty in assessing system boundaries, hidden geographic differences, obsfucatory metrics, and wider ideological debates about energy efficiency on a warming planet. Departing from the norms of such studies, we then discuss the prospects and challenges of relational footprinting, especially in the context of vast regional asymmetries of power and technical capacity. We argue that embracing partial and spatial data could ground more effective and coalitional approaches to the problem.

Current urgencies and difficulties in carbon footprinting the internet

Global networks have grown prodigiously in reach, size, and activity. The amount of Internet traffic tripled between 2015 and 2017, and is expected to double again by 2022 (IEA Digitalization and Energy Working Group, 2017). In the midst of this acceleration, the Internet entered its 'Zettabyte Era,' as the amount of information passing through global networks each year reached 10^{21} bytes. The scale of this system is fast outpacing easy comprehension. By these estimates, it would take more than 5000 years of continuous viewing to watch the amount of video traffic presently passing through the Internet in one month alone (Cisco, 2016).

This rapid growth in data exchange is supported by a commensurate growth in network infrastructure, with a particular boom in data centers. In the last decade, the globally installed base of servers within data centers increased by 30%, while traffic to and from data centers went up by a factor of 11 (Masanet et al., 2020: 985). Throughout this period data center infrastructures have seen particularly massive growth and consolidation within factory-sized hyperscale installations, which now make up more than half of the industry (IEA, 2020).

Capturing an accurate snapshot of a rapidly evolving global sector is a difficult task; a great deal of "data friction" characterizes such efforts. This term, developed within Paul Edwards' (2010) expansive study of climate modeling efforts, describes "the great difficulty, cost, and slow speed of gathering large numbers of records in one place in a form suitable for massive calculation" (80). Data frictions, nevertheless, can be surmounted. Within climate science and politics the problem has been ameliorated through a combination of improved interdisciplinary coordination, sensing, and computational power, won via decades of considerable diplomatic, activist, and public funding efforts (Edwards 2010: 436). The end result is not a frictionless data landscape, but rather one where frictions do not in themselves fundamentally compromise actors' abilities to produce a general consensus. This is a social, as well as infrastructural, achievement.

This has not been the case for the ICT climate assessments. There are ongoing difficulties in acquiring, analyzing, and sharing high-quality data about the sector and remarkably enduring dissensus about research methods and implications. According to different voices in this debate, the carbon and energy costs of the Internet are *growing* (Andrae, 2020; Belkhir and Elmeligi, 2018; Ferreboeuf, 2019; Makonin et al., 2022), *shrinking* (Accenture Strategy, 2015; Aslan et al., 2018; Lange et al., 2020), *holding flat* (Masanet et al., 2020; Shehabi et al., 2018), or even *moving in all directions at once*, depending on how you count (Bieser and Hilty, 2018; Coroama et al., 2014; Court and Sorrell, 2020; Lorincz et al., 2019; Malmodin et al., 2014; Sorrell et al., 2020). Even within peer-reviewed literature estimates regarding the carbon intensity[1] of network transmission vary by up to five orders of magnitude (Aslan et al., 2018). These differences matter; they make consensus on empirical questions impossible and polarize wider public debates.

Footprinting methodologies are thus a primary and underdetermined way in which competing environmentalisms are brought to ICT. Environmental politics, in other words, are often also data politics. Data frictions and controversies abound across 6 key factors: access to industry data, bottom-up vs. top-down assessments, system boundaries, geographic averaging, functional units, and energy efficiencies. We discuss each factor below, before turning to a wider analysis of the debate and new avenues for its future.

Access to industry data

As with many debates about business impacts, there are acute concerns over industry capture, especially when industry funds much of the research. Yet, as the ICT footprinting debates reveal, delineating structural bias is not a simple matter. This is evident in two critical and early sources of carbon footprinting research: the team of Anders Andrae and Thomas Elder on the one hand, and Jens Malmodin and Dag Lundén on the other.

Andrae and Elder promote a degrowth approach. In 2015 they published a highly-circulated study that assessed global ICT electrical usage in the past (2010) and future (2030). Modeling a range of future possibilities with best, expected, and worst case scenarios, the researchers concluded that communication technologies were currently using 1%–14% of global energy resources, and were on track to grow up to an astounding 51% by 2030, corresponding to 23% of global greenhouse gas emissions

(Andrae and Edler, 2015). In this worst-case scenario, ICT energy draw would outpace global renewable energy production, essentially negating decades of energy transition (Andrae and Edler, 2015). This is a portrait of an industry running out of control. News reports (Vidal, 2017) and environmental groups (Ferreboeuf, 2019) quickly popularized the most extreme predictions.

Three years later, Malmodin and Lundén offered two studies with a sharply contrasting perspective, arguing that the energy intensity of ICT was neither growing exponentially, nor even necessarily growing much at all. In these findings, not only had the carbon footprint of the sector largely flattened, but its share of global energy consumption (3.6%) and greenhouse gas emissions (1.4%) was much smaller than previously estimated (Malmodin and Lundén, 2018b: 28). Contrary to Andrae and Elder's fears, they argued that economies of scale and ever-growing rates of energy efficiency warded against environmental overreach (Malmodin and Lundén, 2018a). The industry, in other words, was in fact experiencing a kind of green growth, with economic activity and consumer services outpacing the material impacts of the sector. As they conclude, "it seems that the age of dematerialization has finally arrived" (Malmodin and Lundén, 2018b: 29).

How to account for this sharp difference in findings? One may be tempted to chalk up this departure to industry funding and influence. Malmodin, after all, is a Senior Specialist at Ericsson, a major multinational telecommunications company, while Lundén is the Environmental Manager at Telia, a Swedish mobile network operator. These institutional commitments present something of an obvious conflict of interest, especially given the circulation of their research within industry PR efforts. Ericsson, for example, drew extensively on the pair's 2018 *Sustainability* publication in their 2020 effort to rebut public concerns about the carbon footprint of the sector (many of which were sparked by Andrae and Elder's work), stressing that ICT's energy consumption and carbon emissions were relatively modest, largely under control, and produced net benefits for the energy transition to come (Ericsson, 2020).

However, a straightforward argument about industry capture would miss many of the nuances of the strategic trade-offs required in the pursuit of adequate data. Malmodin and Lundén's studies are able to draw on much more grounded data (anonymized energy consumption figures from an operator questionnaire) precisely because of their proximity to sectoral operations; this data would otherwise not exist in a comparative form. Industry relationships are in this sense generative, rather than limiting. Andrae and Elder, conversely, sacrificed empirical granularity because of their data's projective nature—data that were drawn from publicly available traffic and sales predictions rather than actually existing build-out. Additionally, Andrae and Elder are both employed by Huawei Technologies Sweden, complicating any simple line that can be drawn between employer interest and research outputs.

This demonstrates how, in ICT footprinting, industry entanglements are to some degree both unavoidable and non-determinative. Absent a mandate for public reporting, varying degrees of collaboration with industry very likely continue to be necessary to this line of research for the foreseeable future. As a result, it is not possible to assess the trustworthiness of researchers based on their proximity to industry; a politics of purity (Shotwell, 2016) is not straightforwardly useful in such conditions, complicating how one can make sense of contradictory findings.

Bottom-Up vs. Top-Down Assessments

A further impasse centers on methods for collecting and operationalizing data: a primary distinction is drawn between *bottom-up* and *top-down* approaches. Bottom-up studies, held in higher regard (Koomey and Masanet, 2021; Lei et al., 2021), consist of an inventory of data collected directly from producers or statistical repositories, which can then be simply added and evaluated. This is theoretically the most precise way to conduct a footprinting study, as data are grounded in direct and comprehensive measurements. Where gaps emerge—such as, for instance, unreported energy use or the number of terminals within the scope of a given provider—then a reasonable guess or weighted average can be deduced from data reported elsewhere, such as a direct competitor or a comparable actor in another country.

The goal of the bottom-up analysis is simply to find or create adequate data to compose the whole, yet its completionist ambitions can be a source of weakness. Especially when assessing complex global industries, truly comprehensive datasets often do not exist and cannot be straightforwardly reconstructed. Such efforts look more like patchwork mending than clean reporting: several sources are sewn together, and many more are typically developed through extrapolation. Data variance can consequently be magnified across further extrapolations, resulting in a propagating margin of error. As one pair of researchers summarize, "data… especially for less-frequently researched components and processes, are particularly vulnerable to undetected errors, and current reported results are of an unknown quality" (Teehan and Kandlikar, 2012: S191).

The alternative is to conduct a top-down study: essentially a mathematical model that attempts to demonstrate relationships between variables in a system, such as equipment, data, energy, and greenhouse gas emissions. This approach requires only a single known measurement (e.g., the annual sales of equipment, or the amount of total traffic recorded within a network at a given time) to start. Reasonable numbers can be intuited or averaged for the remaining variables (e.g., how much electricity the equipment requires), resulting in a flexible model of system outcomes. Consequently, top-down studies have the appeal of being better adapted to estimate future trajectories and outcomes.

Yet, this by no means resolves problems of uncertainty within such models. Data can be incorrectly measured or relations between variables might be poorly expressed in a given equation. It is also the case that verifying top-down studies is difficult: outside of critiquing methodological minutia, or simply waiting for time to pass in order to see if future trends bear fruit (at which point the study will be of little utility), it is hard to know how much certainty to give to a given model. Statistical analyses of error margins are not commonly used,[2] resulting in the proliferation of disparate results from disparate methods.

To add further to these tensions, a pure distinction between these two research designs is often impossible to make; because of the fraught and fragmented nature of network data, hybrid studies that combine aspects of top-down and bottom-up assessments are very much the norm. Reconciling findings from both top-down and bottom-up approaches could strike a constructive balance, though in practice one method is most often used to produce data for a given variable that eludes the other. The result is thus often more a give-and-take blend than a checks-and-balances approach. For instance, Masanet et al. 2020's study, which endeavors to correct for a deficit of bottom-up studies, nevertheless draws on Synergy Research Group's Hyperscale Market Tracker and Cisco Global Cloud Index—data that is itself the modeling product of mixed top-down and bottom-up analysis (Dinsdale, 2021).

As a consequence, new studies with differing results fail to win consensus because the validity of the research design seems to be forever in question. This schism is in part a result of asymmetrical access to industry data, but also represents clear disciplinary affiliations. Norms and practices from industrial ecology and macroeconomics validate top-down approaches; those from the network research and corporate accounting fields tend toward bottom-up studies (Schien and Preist, 2014). Paradigmatic differences (Kuhn, 1970) thus appear to be significant barriers to wider methodological resolution.

System boundaries

A further and especially important problem in constructing the environmental footprint of the Internet is that there is no commonly held and wholly defensible definition for where it can be said to begin and end. The Internet is a diffuse sociotechnical assemblage—as Jennifer Gabrys argues, less a determinable number of objects and more a set of intersecting relationships (Gabrys, 2014: 9). Yet attempts to conduct a rigorous accounting of the sector's impact nevertheless require that boundaries be drawn (Barad, 2007: 140). Where to do so is a question the literature has taken up in many different ways, guided by both practical limitations in the data and disparate personal goals.

Most legibly, researchers must define the scope—or system boundaries—of the infrastructures and devices under assessment. This is not a simple matter. In terms of core internet infrastructures, there are not just data centers, but internet exchange points, terrestrial fiber-optic lines and subsea cables to consider. But we need not necessarily stop there. Should consumer devices count within industry footprints? How can double-counting be avoided as data moves across multiple infrastructures? Should more socially marginal (but ever-more impactful) specialized applications like Bitcoin be included? Moreover, are the carbon emissions associated with the production, maintenance, and disposal of a given device really necessary to assess overall patterns, or is a snapshot of the current electrical draw sufficient? One comprehensive literature review published on the field notes that the question of system boundaries is not only highly unstandardized, it also has the greatest effect on the resulting estimates. Recalculating past studies to a common system boundary reduces estimates by up to two orders of magnitude (Coroama and Hilty, 2014: 67).

However, the pursuit of a common boundary may only complicate, rather than resolve, attempts to access suitable data. National-scale analyses may provide the most legible system boundary, given easy access to certain national inventories of equipment as well as the tendencies for network infrastructure to look more alike within the borders of a nation. Yet, this boundary omits the international nature of digital networks, including infrastructures that carry data across continents as well as the potential 'offshoring' of digital infrastructure to distant locales (Pasek, 2023: 31).

Questions of system boundaries also inevitably bleed into questions of responsibility and attribution. This surfaces most visibly in the relative weight put on individual consumers. For example, some studies estimate that 47% (Accenture Strategy, 2015) or far more than half (Malmodin et al., 2014) of all ICT emissions can be attributed to end-users. This has informed some industry efforts to redirect public concern about digital systems into individual behavior modifications (Ericsson, 2020), echoing previous strategies of de-escalation through green (neo)liberalism (Steinberg, 2010). Other efforts, notably those developed by civil society actors, suggest that consumer behavior only constitutes a mere 20% of the problem (Ferreboeuf, 2019: 20), furthering confusion.

Method, as before, explains but does not resolve this divergence. Figures vary widely based on the incorporation or exclusion of a full life-cycle analysis of equipment; network operators and their equipment typically carry a larger share when evaluating use cases, while consumers, in the aggregate, outpace network equipment when production is included in calculations, though this is changing (Andrae and Vaija, 2017). Conversely, consumer terminals take up a dwindling share of the sector in studies that predict the prodigious rise of data center energy impacts (Andrae and Edler, 2015; Belkhir and Elmeligi, 2018). Cloud computing, definitionally, further complicates this picture as it mixes personal data and corporate equipment. The situation is unlikely to clarify itself in the future; boundaries will be enduringly contentious in research design.

Geographic averaging

A fourth and highly influential problem lies in the parallel issues raised by the use of broad global averages, lacking in regional granularity, and in the inappropriate extension of regional data to represent all parts of a global model. Both these tendencies limit the extent to which ecological and energy differences between geographies can be assessed. After all, building a data center in Brazil, where water tables are high and much of the electrical draw of the facility will likely come from legacy hydropower, is clearly a different proposition than building one in Qatar, a desert nation whose electrical grid runs almost entirely on fossil fuels. Yet, the vast majority of ICT footprinting studies do not distinguish between the two.

In almost all sectoral studies, global averages are used at key points in the study design, most commonly when energy use figures are converted into equivalent carbon emissions. This is often the last step of the research process: after an extensive effort to determine the total energy consumption associated with ICT, researchers will simply convert between energy units and the global average carbon intensity of electricity—for instance, 0.623 megatons of carbon dioxide equivalents per TWh (Andrae and Edler, 2015).

This choice dramatically simplifies the conclusion of a very complicated accounting effort. Differentiating international figures on the basis of distinct national (or even regional) average carbon intensity would create considerable difficulty, both in the acquisition of geographically granular data on energy draw and in the final calculation of figures. While the respective carbon intensities of national and regional grids are well known, nationally-specific ICT energy demand is often not public knowledge (nor necessarily known by any single actor within the industry). This challenge is in part specific to ICT and the global nature of the Internet: because of the proprietary and sensitive nature of networked data exchange, the relative global flows of traffic across the state, private, and corporate channels are difficult to quantify, let alone model. Yet this problem is also symptomatic of a broader trend in footprinting studies overall. Regional and temporal disparities are routinely ignored in the pursuit of more readily accessible accounting standards (Blakey, 2021; Lippert, 2015). The norms of the trade readily endorse such shortcuts.

Despite the practical advantages of using simple average figures, this tendency diminishes certainty and accord within the ICT footprinting subfield. For one, the specific global average carbon intensity of electricity is not standardized across the literature and has shifted significantly over the past decade as the grid has decarbonized (Cox et al., 2018). As such, differences in the given conversion rates or projected rates of future decarbonization can account for some of the variability between studies. Even more importantly, the use of broad average figures ignores regional differences, which is concerning given the disparities in renewable energy production and ICT build-out across different national contexts (Greenpeace East Asia, 2019).

In other instances, partial data are used as if they were global averages. Most such cases stem from the patchwork nature of data inventory construction, which frequently draws on industry connections within researchers' professional networks. As these researchers are almost entirely from the Global North, this can risk universalizing data from non-universal corporate practices. For instance, environmental performance data from Google might stand in for all data center infrastructures outside of North America and Europe (Masanet et al., 2020), or employee air travel data from Google and Facebook might be used to benchmark trends across the ICT sector as a whole (Malmodin and Lundén, 2018b). In other instances, national averages, instead of regional grid data, are used to assess the carbon intensity of network operations (Carbon Trust, 2021; Masanet et al., 2020). This is especially concerning in the case of the USA, where regional disparities in clean energy standards between states are a significant factor shaping the carbon footprint of major network operations (Cook and Jardim, 2019; Pasek, 2019). Overall this trend disguises sharp differences in the climate impacts of local grids and energy regulators—differences that could significantly affect the outcome of such studies and the policy measures they might inspire.

Finally, though beyond the scope of this study, we note that the possibility of embedding environmental inequities within the results of carbon-centric research. A "carbon reductionism" (Moolna, 2012) that values only CO_2e as a metric of harm risks ignoring regional disparities in digital access and climate (Starosielski, 2021), as well as disruption to culturally or ecologically significant lands. More locally embedded social research could ameliorate this problem. Additionally, observations about regional electrical grids could also be extended to differences in local watersheds and land scarcity, as data centers have significant land and water footprints (Ristic et al., 2015). Obringer et al. (2021) are an early team making such attempts, though not without criticism (Koomey and Masanet, 2021).

Functional units

Further differences in measurement and conclusions arise from the specific metrics used in these studies' key findings. In contrast to other debates, there is at least some degree of standardization in the literature on this question. Most papers assess the energy impacts of digital networks through the relation of kilowatt hours of electricity (i.e., the number of kilowatts a system draws within an hour's time) and gigabytes of data passing through the network. This is routinely expressed as a functional unit: the KWh/GB.[3]

This unit has the advantage of being a relatively straightforward calculation from the kinds of energy data collection that characterizes both top-down and bottom-up methods. The sum quantity of electricity required to power a system can be simply divided by the sum quantity of data circulating within it, resulting in an assessment of energy efficiency. This method can then be applied comparatively to assess the relative intensity of different infrastructural components within a network (Coroama et al., 2013) or changes over time (Andrae and Edler, 2015; Malmodin and Lundén, 2018a).

Yet KWh/GB ignores a central feature of network operations: The relation between energy draw and data exchange is not linear (Koomey and Masanet, 2021). This is because network operations have largely fixed rates of energy draw, regardless of how much data is moving through network exchanges at any given moment. Unlike data centers, which are increasingly adapting to adjust the amount of infrastructure that is powered during peak vs. off-peak hours, network equipment is almost always on, requiring the same amount of energy to run.

What's more, network infrastructures are routinely installed with excess capacity. Because the regulatory and construction requirements of laying new fiber or transceivers are considerable, the industry overbuilds at the beginning of a system's lifespan instead of regularly unearthing and upgrading it. A fiber optic line will therefore see improvements in energy efficiency over the course of its expected lifetime simply by virtue of the increased amount of data moving through the network. In this way, it appears to grow more sustainable year after year.

It's also the case that the KWh/GB effectively disadvantages the apparent performance of industry actors in certain parts of the world. Data centers in Singapore, for example, have a much higher energy draw due to the greater need for air-conditioning than data centers in Finland, and will thus appear to be inherently less environmentally friendly (Starosielski, 2021). This outcome is also evident in assessments of small regional contexts that lack the scalar capacity to achieve the energy efficiencies of hyperscale datacenters or network infrastructure running near capacity. Network providers in small island nations, for example, frequently have particularly acute gaps between maximum and actual use because of the scalar economies of the sector, and the ways in which islands frequently act as hops within systems that bridge much larger markets. As a result, this functional unit lends itself toward efficiency-based policy targets that may work to reinforce, rather than challenge, extant global inequalities in the distribution of digital resources. To the extent that this metric dominates research designs within the literature, the literature is poorly equipped to assess the nuances of network infrastructure lifecycles and regional digital divides.

One alternative metric is the KWh/subscriber: a way of dividing the larger energy draw within a study's system boundary by the number of subscriptions within the network (i.e., the number of unique Internet/mobile/telephone/cable connections). This metric has the potential to better capture global trends in the expansion of network access over time. As the number of people online increases, the energy demands of the Internet will also increase, so these relations are highly correlated—in many cases to a greater degree than KWh/GB (Malmodin and Lundén, 2018b: 25).

Accordingly, a subscription-based metric points to questions of digital access and, consequently sociotechnical and socioecological problems of communication equity in the way it measures energy or carbon footprints. Yet it does not do so perfectly. The metric may also disguise asymmetries between users in the Global North and South, urban and rural contexts, and other enduring digital divides. Less-connected populations typically gain access to personal network subscriptions through data-constrained mobile devices, while socioeconomically advantaged groups consume an increasingly sizeable share of data. Subscribers/KWh thus has the potential to disguise the outsized draw of elite users through the expanding userbase overall. Disentangling different regional and classed patterns in subscriber data and energy use is possible, but like the question of regional carbon intensities of energy, would be a highly complicated endeavor.

Energy efficiency

A final and significant unresolved question in the literature concerns the future rate of energy efficiency gains within global networks, particularly at data centers. Like the relative size of the sector's footprints, there is no consensus on the rates of improved KWh/GB efficiencies in the future, nor the extent to which such efficiencies are an adequate way to frame and manage the climate impacts of the sector as a whole.

One camp within the literature represents a techno-optimistic perspective, inflected by the exponential scaling of Moore's Law.[4] Jonathan Koomey, a long-contributing researcher in this field, observed a decade ago that the efficiency of peak-output performance computing doubled every 1.5 years (Koomey et al., 2011). Given the correlation between performance and electrical draw in data centers and consumer terminals, "Koomey's Law" suggests that ICT's total energy (and therefore carbon) footprint would improve as a natural extension of industry trends. Moore's Law, in other words, was a law of green growth. Indeed, even absent a coordinated regulatory or industry framework, the energy intensity of data centers has shrunk by about 20%/year since 2010, leading the International Energy Agency (IEA) to predict that the industry will both significantly grow in size and shrink in energy demand within developing markets like India. These markets are, in the future, expected to follow the hyperscale trends set by the USA and thus are assumed to be already on track to reduce the KWh/GB of their operations (IEA Digitalization and Energy Working Group, 2017: 107). This is a portrait of infrastructural growth decoupled from environmental impacts—a rare occurrence in contemporary economics.

However, like Moore's Law, the long-term viability of Koomey's Law is highly questionable. Energy efficiency, like transistor size, is hostage to the physics of silicon semiconductors: there is a limit to how small these basic units of computation can become before their functionality is compromised. The improving energy efficiency of the sector, therefore, is to some degree meaningfully tied to its rate of chip densification and therefore techno-optimistic predictions about the unknown. In the meantime, Koomey's Law has already begun to show some cracks. Around 2000 peak-output efficiency slowed, such that the metric now takes 2.7 years to double.

Yet Koomey is not overly perturbed by this development. He has since revised his trend analysis to instead consider "typical-use efficiency," which calculates energy performance throughout the course of a device's use (inclusive of idle and underused periods). Under these altered conditions, the 1.5-year period still holds, driven by advances in data center and personal device energy-management trends (Koomey and Naffziger, 2015). In this way, design choices and algorithmic energy-saving routines have sustained rates of improved efficiencies even in the context of a wider sunsetting of Moore's Law (Lorincz et al., 2019). This has led others to refer to future potential energy efficiencies as a "resource" that the sector can draw on to "absorb the next doubling" of data within digital networks "with a negligible increase in global data center energy use" (Masanet et al., 2020: 985). Beyond this horizon, further efficiencies might also be found through a combination of regulatory incentives and reforms, including procurement standards, public R&D investment, and a wider state-sanctioned energy transition (Masanet et al., 2020: 985–986). This resource is to a large degree speculative, and thus promissory to its proponents.

Other researchers forward a much more pessimistic portrayal of energy efficiency's role in the management of ICT's climate impacts. Some simply believe that the growth rate of the sector will directly outpace energy savings in short order—that Koomey's Law won't be able to counterbalance a rapid spike in overall demand (Andrae and Edler, 2015; Ferreboeuf, 2019). Others come to a similar conclusion through a different path: attempts to integrate full life-cycle analysis into assessments of ICT's overall impacts suggest that an innovation cycle characterized by the rapid replacement of older equipment with newer, slightly more efficient devices disguises a much larger embodied carbon footprint in the servers headed to recyclers (or to landfill). Integrating these figures into system models has the potential to dramatically shift the balance of findings (Belkhir and Elmeligi, 2018). Similarly, while frequently excluded from system boundaries, growing trends in resource-intensive operations such as AI development, blockchain, and IoT present additional and unpredictable sources of energy growth for the sector (Andrae, 2020).

These cases also point to the possibility of efficiency rebound effects. The specter of Jevons Paradox guides these assessments, which attempt to construct system boundaries wide enough to monitor counterfactual or supplemental consumer behaviors in the face of more efficient resources. This branch of the literature is much less empirically precise, though it does suggest that the increased aggregate use created by less expensive (and seemingly green) digital technologies is likely to cancel out, if not outpace, the efficiencies won through steady energy efficiency improvements (Andrae, 2021; Coroama et al., 2014; Court and Sorrell, 2020; Freitag et al., 2021; Zeadally et al., 2012). A politics of degrowth follows.

Toward relational footprinting

As sociologists of quantification explain, appeals to numeric authority and commensurate metrics often appear "at the borderlands between institutions" where uncertainty about values, methods, and overall political strategy frequently upend traditional assumptions and deliberative processes (Espeland and Stevens, 1998: 332). Cutting across national jurisdictions, public and private data, and vast global abstractions, the ICT sector is a borderland par excellence. As demonstrated above, data frictions, gaps, and generalizations make it incredibly difficult to create a universal methodology for a global industry. We are left with incommensurate findings and political demands: A binary between techno-optimistic efficiencies or techno-pessimistic degrowth.

This prompts us to ask: What if this debate will never be empirically resolved? What if the global footprint of the industry is something that we cannot ultimately know? The history of environmental struggle demonstrates the risks of relying on expert consensus to decide political claims (Murphy, 2006) or indeed the adequacy of any single assessment metric in making all claims legible

(Blakey, 2021). How, then, might the environmental politics of ICT be productively advanced without global certainty? What alternative strategies of enumeration can be pursued that are more partial—and thus perhaps also actionable?

We find one such alternative in an approach that we call *relational footprinting*: an empirical and strategic orientation toward demarcating particular relationships between elements—geographic, spatial, technical, and social—within a broad infrastructural network.[5] This relies on the acquisition and comparison of data specific only to nodes of interest within a complex network of interconnected socio-technical components. Rather than seeking to evaluate sectoral performance as a whole, and thus overcome vast data frictions in assessments at a global scale, relational footprinting identifies specific differences between discrete and measurable local elements and suggests how these differences might be leveraged for climate mitigation.[6] Relational footprinting thus seeks to take the patchwork nature of ICT's borderlands as an opportunity, rather than limitation, to the question of green ICT.

One particularly evident factor to this end is the difference in the carbon intensity of regional energy grids. Instead of calculating a global KWh/GB or subscriber, a relational approach would inventory the carbon footprints (as well as water and land footprints) of powering data centers in specific parts of the world. (So too might we consider comparative regulatory and market environments for directly provisioning such systems with renewable energy). Vast asymmetries will be readily evident: different locations are further along the course of decarbonizing their electrical grids, and different energy and cooling needs obtain in different regional climates. These differences could be generative. To return to a prior example, locating a data center in Brazil will likely be better than in Qatar. What's more, evaluating this question only requires discrete local datapoints (energy load and regional electrical carbon intensity), which can be determined through common and uncontroversial datasets. Data frictions are thus significantly easier to overcome.

Relational footprinting can also be applied to relative energy use across different parts of the Internet's technical infrastructure. Our approach to this question is grounded in our wider research team's efforts to conduct a carbon footprint analysis of the subsea cables that are a small but essential part of the global Internet. These cables carry more than 95% of transoceanic data traffic, making the world wide web true to its name (Starosielski, 2015). Nevertheless, cables' energy and climate impacts are relatively insignificant: by the few estimates available, they compose only a fraction of a percent of the sector as a whole (Coroama et al., 2013; Malmodin et al., 2014). As a result, most studies omit cables altogether, viewing them as a negligible data point—something of a rounding error. In universalizing footprints, subsea cables are not significant enough to merit serious inquiry.

By contrast, in relational footprinting of ICT, subsea cables play an important role precisely because of their negligible impact. The promise of subsea cables is that the climate costs of moving data are slight. Resultantly, mitigation can be newly posed as a spatial problem: if the carbon intensity of data derives predominantly from its location, rather than its distance, then the 'where' of ICT becomes a modulating factor to its size. From this perspective, networks might be re-configured to leverage more intense development in renewably-powered locations and degrowth in fossil-fuel-based locations (say, to connect more data centers in Brazil and less in Qatar). Emissions can thus be lowered, with certainty, and without first winning global support for a dramatic endorsement or curtailment of industry business models or the value of particular forms of digital content. Network shapes, rather than scales, offer new prospects for assessing the present and future Internet.[7]

What's more, the political gains of such a strategy might go beyond the carbon reductionism of a global footprint held in check, and touch more expressly and productively on a range of regional social concerns. The comparisons that relational footprinting highlights will invariably exceed carbon accounting metrics, and can be used to open up wider discussions of digital and economic divides between nations. To take one example, subsea cables require long-term coastal investments where international data is territorialized (typically 25-years). Unlike the flexible, often impermanent deployment of data centers (Pasek, 2019; Velkova, 2019), placing cable landing stations is a highly consequential, durational investment. They are places where multinational corporations must meet local regulatory requirements, as well as places where geographical and financial affordances can be mapped and routed in the development of new infrastructures (Starosielski, 2015). In this way, unexpected locations—small island nation states, rural counties, and megacity ports alike—can form the backbone of international industries and hold critical importance in the routing and management of data.

Relational footprinting thus helps to shift perspectives to local scales and challenges. A geographic turn in network analysis shows how cables' coastal footprints (and potential pathways for climate change mitigation) are already entangled with Native Hawai'ians struggling for energy and national sovereignty on the coasts of Oahu; Bermuda or Puerto Rico as post-colonial vestiges of transatlantic and trans-American circulations; rural Irelanders' experiences of energy price hikes while new data centers are vying to be built on their landscapes; and the 2Africa cable plan to build a ring around the "untapped" digital markets of Africa. It also highlights the disproportionate vulnerability to sea-level rise and extreme weather events faced by communities in such coastal and island locales. Wherever cables come ashore, they enter into eco-political conjunctures.

ICT can be a force or a resource in determining such questions in any number of ways. While, within universal accounting models, these sites remain on the margins, a few small nodes among many larger ones in a global system, from a relational perspective they are key points of influence and potential investment. By heightening the importance of space in network development, local concerns take on global import. Actors and movements that mobilize the strategic value of local nodes within greener network formations will be better able to advance both equitable development and coastal resiliency.[8]

A relational approach, however, is not without complications. It does not offer a linear path for the aggregate monitoring and management of the sector, as might be contemplated by United Nations initiatives or the International Telecommunication Union. In prioritizing renewable energy, it risks marginalizing countries with dirty grids for reasons of colonial underinvestment, as well as ignoring the grid and land use conflicts that often occur around renewables in areas of rapid regional expansion, where ICT plays an ever-greater guiding role (Bresnihan and Brodie, 2020; Libertson et al., 2021). There are also further issues of privacy and control: While it may make more sense from an environmental perspective to route one's data internationally through Brazil, this comes with a cost to data sovereignty and latency. Accordingly, we urge scholars and stakeholders to pursue relational footprinting's emphasis on local conditions expansively, looking for coalitional concerns that can shape the climate trajectories of the ICT sector through questions of equity, access, and regional development and determination, rather than focusing on the carbon alone (Baker, 2021).

This is to say that relational footprinting does not so much avoid the political conflicts raised by degrowth vs. decoupling debates, but situates them in more contingent and productively delimited scales. ICT growth may be a means for some communities to win more economic and infrastructural investments and accelerate the pace of local energy transitions. Elsewhere, it will doubtlessly find opposition, prompting concessions from big tech in some cases, and in others, retreat. Through its emphasis on partial perspectives, relational footprinting situates climate politics in place, where solutions and contestations need not be managed from above, but can instead be negotiated on the ground, opening up many thousands of terrains in which climate coalitions might be forged, and in which direct steps can be taken. It does so by insisting on the value of local, relational, and commonly known data, as well as the importance of using data to open, rather than determine, political debate.

Conclusion

Digital media and critical data studies are currently well into an infrastructural turn—one in which environmental politics are ever-more urgent sites of analysis. Our paper shows that these environmental politics are multiple, and deeply embedded in unsettled questions of measurement and scale.

Throughout this study, we are reminded of Ted Porter's famous observation that the credibility of numbers is a profoundly social problem, created and sustained by groups that often lack the public legitimacy and internal unity necessary to democratically resolve conflicts within and between institutions (Porter, 2020: 220). The politics of quantification, as media and STS scholars demonstrate, present opportunities to open or foreclose potential futures (Shapiro et al., 2017). It should therefore come as no surprise that assessments of the climate impacts of ICT are so intertwined with disparate visions for the sector and its technologies—the future of which has yet to be decided.

Yet it would be crude to suggest that data is wholly socially malleable, and that all actors in this wider empirical and political debate make equal and easy use of numbers to their own ends. The task of acquiring and assessing figures about globally dispersed digital networks is hindered by ongoing data frictions, both in the compilation of data inventories and rapid shifts in the dynamics they seek to represent. Scholars overlook these complexities when they uncritically draw on the charismatic numbers of a single study. The wider degrowth vs. decoupling debate, and the methodological terms on which it is failing to progress, are also important sites of social analysis.

While the question of the carbon footprint of the global ICT sector is ongoing, and without dismissing the value of continuing to grapple toward more precise empirical answers or the social goods offered by contested visions of economic growth, our contribution has been to both moderate hopes for quick resolution and to provide an alternative approach to environmental action predicated on the partial data known to us today. By examining regional and relational differences, industry and activists alike can develop strategies toward networks that are differently connected across spatial and energy divides, with direct and meaningful mitigation benefits. Relational footprinting is thus suited for a different kind of politics: one that is coalitional, emplaced, and that sticks with rather than reduces the diverse and rapidly shifting relationships between the social demand, resource use, and operational acuity of global networks.

Highlights

- The global carbon footprint of the ICT sector is a topic of enduring debate.

- This debate is unlikely to be resolved soon due to ongoing data frictions and incommensurate methodologies at the global scale.
- Instead of a complete accounting of ICT's climate impacts, relational footprinting offers new avenues for action.
- Relational footprinting aims to identify differences between system elements that can be leveraged with only partial knowledge.
- Subsea telecommunication cables, in particular, could be leveraged to reduce the climate impacts and regional inequities of global ICT.

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Notes

1. Carbon intensity refers to the amount of greenhouse gases associated with a measured activity. It is commonly expressed in kilograms of carbon dioxide equivalents.
2. See Schien and Preist, 2014 for a rare exception.
3. This can be scaled down to J/B or up to TWh/GB.
4. Moore's Law describes a joint economic and material trend in the semiconductor industry, and thus ICT as a whole. It holds that the number of transistors on a microchip will double every two years, while the cost of the components will be halved.
5. A brief note here on fellow travelers in this semantic field: there are now several parallel efforts to conceptualize more relational approaches to accounting, accountability, and sustainability. In economics, relational accounting describes an approach to assessing the often moral, familial, and gendered character of financial dynamics (Zelizer, 2012). A similar but distinct approach is evident within Indigenous and post-colonial theorizations of reciprocal responsibilities to human (and often non-human or ancestral) kin, moving at timescales and through social exchanges that are necessarily resistant to mainstream academic project management goals and, at times, the abstractions and equivalences germane to quantitative metrics (Moncrieffe, 2011; TallBear, 2019). Sustainability studies and its allied interlocutors in the fields of management and modeling have also grappled with the need to prioritize contextual relations and responsibilities (McElroy et al., 2008), and in one case have offered a preliminary vision of 'relational footprinting' as a potential means for quantifying the sustainability of an organization's natural, social, and financial flows within wider interrelated systems (Hadders, 2015: 12). Our mobilization of relational footprinting is thus part of a wider shift in social critiques and remobilizations of insular, data-oriented metrics. While we mean something quite specific in our development of relational footprinting within this paper (an emphasis on the generative differences between discrete nodes within a wider system which need not be wholly modeled), we wish to highlight this shared movement against and within processes of quantification. Across these differing approaches it is clear that *relative* difference is itself an insufficient goal of inquiry, and that the turn to the *relational* tends to imply greater, if still underdetermined, moral entanglements and epistemological horizons which complicate the sufficiency of quantitative metrics alone. What matters is not necessarily what we measure, but how measurement opens or forecloses forms of responsibility and reciprocity within interrelated systems.
6. Relational footprinting thus borrows from and modifies the methods and metrics of previous sustainability assessment tools. Like ecological footprinting and the energy-water nexus, it situates resource use in the context of a relational system with competing pressures and potential trade-offs. It resists, however, the need to fully model these dynamics within a universal accounting of natural capital stocks. Instead, it deals in discrete units of measurement (such as carbon or water footprints), while also insisting that these data inventories ultimately be brought to comparative use. Like complexity science and its cybernetic antecedents, relational footprinting can aid in the study of interacting systems with emergent behaviours, though its aims are much more modest: not to model the direction of the whole, but to illuminate discrete and quantifiable points of intervention. Our aim here is not to replace these tools (indeed they are highly valuable) but to suggest that there are often epistemological trade-offs between depth and breadth in contexts like ICT, and so new political possibilities might be opened through a reconfiguration of their aims.
7. Early examples of this logic are evident in the development of energy-responsive load shifting protocols in both big tech (Google, 2020) and small (Brain et al., 2022). As these examples suggest, time is also a modulating factor, given the circadian and seasonal rhythms of renewable energy production.
8. Moreover, a relational footprinting would also be poised to assess the relative differences between the sectors of core internet infrastructure—data centers, IXPs, and cables—and to move forward in ways appropriate to each's unique technical and political landscape. For example, IXPs are relatively immobile nodes located where data traffic cables are localized, and which often have regional significance. For this reason, clustering together IXPs as one might cluster data centers may not make sense technically or politically, even if it were to offer positive climate impacts.

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