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Greater Than the Sum of its Parts: Exploring a systemic design inspired responsible innovation framework for addressing ICT carbon emissions

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The carbon footprint of the world's Information and Communication Technologies (ICT) is growing at an alarming rate, giving rise to calls for tools and methodologies for reporting on carbon emissions towards greater accountability within the sector. Accurately calculating the emissions of digital technologies is a complex task where there are no clear standards for methodologies or boundaries for what should be included in these calculations. Nevertheless, a number of online carbon calculators exist to quantify carbon emissions of ICT. The starting question in this paper is how much such tools can inform and provide insight to people working with ICT innovation to take action to reduce the environmental impacts of the products, services and systems they create. To explore this question, we analyse ICT carbon calculators from a digital innovation designer's perspective, exploring what they enable those creating ICT to see and understand, as well as the limitations of these views on carbon. We argue that these approaches are limited and that a better way to address the issue is by moving from designing carbon calculators to co-designing a framework for responsible innovation that enables systems thinking, exposes complexities, helps with the assessment of carbon emissions without fixating on numbers, and supports evaluation and visualisation of future scenarios.

KEYWORDS: sustainability, climate change, carbon emissions accounting, digital technology, responsible innovation, co-design, systemic design

RSD TOPIC(S): Technological Entanglements

Introduction

Climate science calls for global net zero emissions by 2050 to avoid catastrophic warming (Masson-Delmotte et al., 2018). To achieve this, all sectors must transform to gain significant net reduction in fossil fuels and hence carbon emissions.[1] For the information and Communication Technology (ICT) sector, achieving net zero by 2050 requires the reduction of greenhouse gas emissions by 45% in 2030 compared to 2020 levels (ITU, 2020). ICT creates a carbon impact at each stage of its lifecycle: through the embodied emissions in its manufacturing and transport to the business or user, in its use phase and maintenance, and from its end-of-life emissions as it is disposed of (Freitag et al., 2021). Totalling the world's ICT carbon impacts shows that the ICT sector's emissions are not small but rather at a comparable level to those of the airline industry (Freitag et al., 2021).

Meeting such targets requires urgent and radical change to digital technology as we know it, particularly as the ICT sector's pattern of growth and emissions is increasing at a rate unimaginable in other areas of the global economy. Take cryptocurrency, for example. Bitcoin's emissions quadrupled in 2018 (Stoll et al., 2019), with estimates of Bitcoin's mining network having comparable emissions to entire countries such as Hungary and Switzerland (de Vries, 2019). Another high growth trend is Artificial Intelligence (AI): despite the rhetoric of AI's unique potential to mitigate climate change (e.g. Crown, 2022; Degot et al., 2021; European Commission, 2021; Minevich, 2022), within a marketplace that rewards "compute maximalism", the amount of computing power needed to train AIs is increasing ten-fold yearly (Crawford, 2021) (cf. Schwartz et al., 2020). Renewable energy for ICT infrastructure, such as data centres, will certainly support the net zero transition for ICT, but growth trends such as these in

[1] We use the terminology of "carbon emissions" throughout as a shorthand for CO2 equivalent, meaning the amount of carbon and other greenhouse gas emissions

cryptocurrency and AI are not without consequence: renewable energy has a carbon impact within its infrastructure and supply chain, there are limitations to renewables such as scarce resources for solar panels, and ICT cannot commandeer the global renewable energy supply as this affects other sectors' ability to meet their net zero targets (Freitag et al., 2021).

Although ICT has seen significant and continuous efficiency improvements within its operations, these cannot curb the sector's emissions alone. Efficiency improvements focus on use-phase energy demand and emissions, thus neglecting the greater emissions impacts of manufacturing the machines that make up the computational infrastructure (Gupta et al., 2022; Williams, 2011), not to mention the various environmental harms associated with their manufacture and disposal (Crawford, 2021). Moreover, efficiencies lead to growth in demand for ICT as suddenly, more output can be delivered with less compute and energy consumption, meaning any emissions savings are offset, and in the worst-case scenario, emissions actually increase overall. This is a pattern described as the *rebound effect* (Widdicks et al., 2023), and evidence shows that further innovation and adoption of digital technologies is unlikely to suddenly buck this trend given the historic growth in ICT and its emissions regardless of the efficiencies it has introduced (Freitag et al., 2021).

Meanwhile, there is a strong appetite within policymaking circles for a more rigorous accounting of the carbon impacts of ICT (Knowles, 2021). The European Commission, for example, has established a European Green Digital Coalition to develop a methodology for measuring the "net impact"[2] of digital technologies to guarantee that its Green and Digital Transformation yields the emissions reductions required to meet European climate targets (European Commission, 2022). Similarly, the Body of European Regulator of Electronic Communications' Sustainability Working Group has also called for more data and common methodologies for calculating ICT's carbon emissions, providing "relevant public authorities with more granular and reliable information to support their decision-making" in regards to ICT and sustainability (BEREC, 2022). Such demand is answered by a plethora of carbon calculators, tools used by individuals and organisations to assess and report their carbon emissions and to plan on how to reduce

[2] In broad strokes, this would be avoided emissions enabled by the technology minus its own footprint and potential associated rebounds effects.

them. Some can be found free to use online or are provided to users alongside services they subscribe to, such as cloud computing.

The complex issues identified above call for a systems thinking approach (Checkland, 1999; Meadows et al., 2009; Monat & Gannon, 2015) to minimise the emissions and environmental impacts of ICT innovations. A systems thinking perspective adopts a holistic view, taking into account the various components within a system and their relationships, as well as how they relate to other systems. It makes comprehensible the dynamics of the parts of the system and how they evolve and change over time. It also exposes the mental models of those within the system, giving a human context that goes beyond numbers. In design, the interest in systems emerged as a response to dealing with complex and wicked problems (Rittel & Webber, 1973), moving beyond the traditional fields of design (i.e., communication and products) into services and systems (Buchanan, 1992, 2001; Golsby-Smith, 1996; Mortati, 2022). Recently, the Design Council updated its widely-used Double Diamond model of the design process (Ball, 2019) with a systemic design framework (Council, 2021). The emerging field of Systemic Design sits at the conjunction of design and systems thinking and practice (Sevaldson, 2017; Sweeting & Sutherland, 2022) and provides design principles, methods and tools that could support sustainable and responsible innovation in ICT.

Our study aims to understand how best to support innovators designing digital technologies working to reduce ICT carbon emissions. Are the tools currently available fit for purpose, and if not, how could this be addressed? To investigate this, we reviewed carbon calculators to uncover what information and insights they provide to those innovating in ICT to support carbon emission reduction. We proceed using the following stages. First, we explain how carbon emissions are calculated. Next, we explore what existing off-the-shelf carbon calculators do, followed by a critical analysis of the extent to which they serve the demand for accountability on ICT emissions, specifically where they fall short of providing the kind of information needed to design lower-impact ICT and make decisions about carbon reduction priorities across the ICT sector. We then explore how a systemic design approach could offer different and broader perspectives on how to make sense of and deal with the carbon emissions of ICT. We end by discussing the need for an approach to ICT sustainability that goes beyond calculating carbon and calls for more research on how a framework approach could utilise the kinds of evidence that carbon calculators can provide while productively managing the complexity that these calculators typically lack.

Overview of calculating ICT's carbon emissions

There is a need for concrete numbers on ICT's carbon emissions, but providing this is no mean feat. Current estimates of ICT's emissions (Andrae & Edler, 2015; Belkhir & Elmeligi, 2018; Malmodin & Lunden, 2018) range between 1.8-3.9% of global greenhouse gas emissions, differing due to various considerations of what classes as ICT and its carbon impact (Freitag et al., 2021). Specifically, variations occur due to the scopes of emissions considered (crossing scopes 1–3), as well as what is counted as ICT given how embedded digital technology is within society (e.g. whether TV and blockchain are the ICT sector's problem or whether they are better placed in the entertainment and financial sectors respectively instead) (Freitag et al., 2021). Further complicating matters is the existence of different methodologies used to calculate carbon (e.g., Life-Cycle Analysis (LCA), Environmentally Extended Input Output), and how ICT rebound effects can be considered in these methodologies given they cross boundaries and cause feedback between systems and sectors (Coroamă & Mattern, 2019; Pohl et al., 2019; Widdicks et al., 2023). There is also a multitude of variables which impact calculations, such as undefined boundaries for what is included in each calculation (i.e., data transfer when viewing a web page, data centres hosting websites, end-user devices, the infrastructure of networking cables that transmit the data), how and where data is processed or stored and the infrastructure involved, as well as the type of energy used based on the ICT's geographical location. These complexities and the vast differences in the available estimates of ICT's carbon emissions are thus a good indicator of just how challenging it will be to arrive at an agreed calculation methodology (Knowles et al., 2022).

Despite the academic community being unable to agree on concrete estimates, boundaries, and methodologies for ICT's carbon emissions, many carbon calculators are publicly available and purport to measure these emissions, ostensibly satisfying the demand for this kind of insight. Carbon calculators exist for all sorts of activities, but the focus of this paper is on ICT carbon calculators that we define as a tool to quantify the carbon impacts associated with digital technologies including products, services and/or their use. Knowing that there is huge uncertainty regarding ICT's impacts whilst also noticing the emerging growth and use of ICT carbon calculator tools, we question: Do these calculators actually provide useful information for ICT organisations to meaningfully account for their impacts—specifically for if or when reporting of these impacts becomes the expected practice in the sector? What do they reveal regarding the hidden complexities surrounding carbon accountability for the ICT sector? And looking beyond accountability to responsibility, do these calculators offer meaningful windows onto how to make the most "sustainable" decisions in designing or regulating ICT products and services? In what follows, we explored these questions through an analysis of ICT carbon calculators.

Analysis of ICT carbon calculators

This section explains the methods used in analysing ICT carbon calculators and describes our findings, identifying a typology of four groups of ICT carbon calculators. We searched online for "carbon calculator" or "emissions calculator", using a combination of three academic databases, GitHub and Google, to gather an overview of carbon calculators available to various audiences, including the academic community, software developers and the general public. This was not a literature review but a search more in line with research for design (Frayling, 1994) aimed to scope existing carbon calculators and to identify exemplars that explain how ICT carbon calculators work and offer insights for future design of sustainable ICT. We looked for variety and discounted calculators similar to other examples already collected. Our selection criteria comprised: (a) the calculator needed to follow our definition of an ICT carbon calculator, meaning the carbon calculator needed to partially or solely consider ICT in some way; and (b) the calculator needed to disclose some information about its methodology so that we could scrutinise its functionality (even if only some aspects were present. i.e., data sources) leading to a final set of 20 ICT carbon calculators. A full list of these is available in the Appendix.

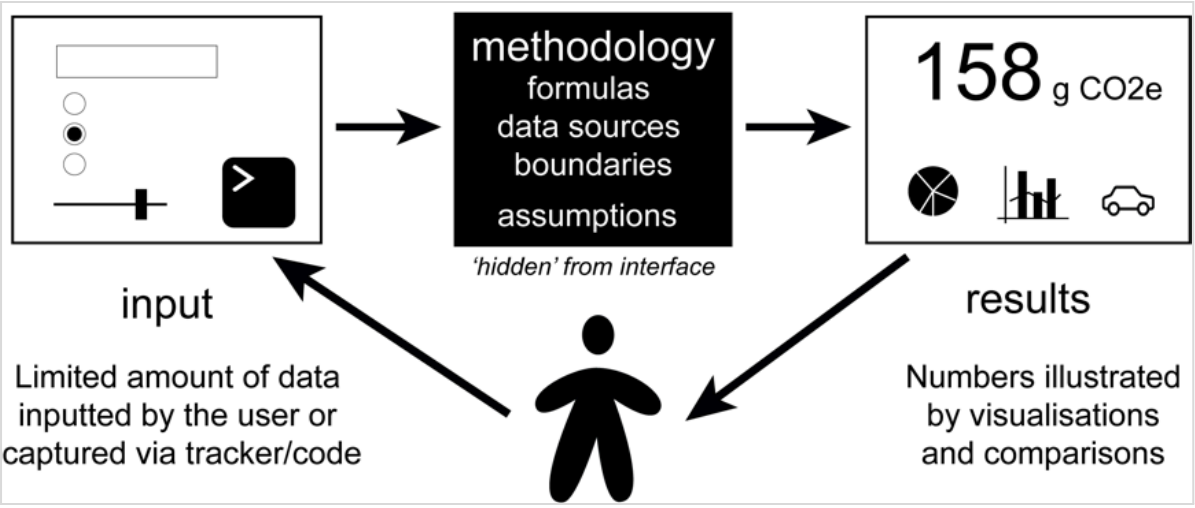

*Figure 1: SEQ Figure * ARABIC 1. A visual model of the structure of an ICT carbon calculator.*

We then conducted a qualitative-directed content analysis (Hsieh & Sarah, 2005). The content of the interfaces, the information they produced, and the documentation provided for each carbon calculator was analysed based on predetermined categories identified from literature (i.e., boundaries, data sources, and formulas (ITU, 2018). Our analysis focused on the following elements:

- What device, function, or activity was the calculator purporting to measure? For example, the emissions of a website, cloud computing, an algorithm, etc.
- The interaction and interface of the calculator, including how users access it, how they are expected to input information, and how results are presented to them
- The methodology underpinning the calculator, including carbon calculation formulas, system boundaries and data sources, as well as any assumptions made
- The stated motivations for producing the calculator
- The type of user the calculator has been produced for
- The solutions offered to users (if any) for addressing ICT's carbon emissions

Our findings indicate that ICT carbon calculators are comprised of three parts: data input, calculation, and the results output. In general, the calculators offer an interface (i.e., web page) where the user inputs information about a given ICT device or service or where data is automatically captured by a code or software tracker measuring energy usage, data transfer or IP location. Parameters for the calculation—specifically the methodologies including formulas, as well as any assumptions made or boundaries drawn—are 'hidden' from the main view, with calculations running in the background. The calculation results are presented as a numeric amount of CO2e and are sometimes accompanied by visualisations, comparisons to other carbon-emitting activities and advice about reducing carbon emissions. A model summarising the structure of ICT carbon calculators is shown in Figure 1. While there were similarities in the ICT carbon calculators' design as described above, there were key differences between what carbon emissions they were calculating and how they approached this. Table 1 describes four types of carbon calculators identified in our study.

Table 1. Four types of carbon calculators were identified in the study.

Carbon Calculator Type	How carbon was calculated for ICT	What information does the calculator provide	Who was expected to use the calculator	Purpose of the calculator	Numbers in our cohort[3] and the examples
Calculation based on the power usage for computation	Data on the amount of time and equipment used in performing certain computation tasks is inputted by the user or automatically collected by a tracker or code. This information is then converted into CO2e based on the carbon intensity of the energy grid in the geographic location where computation is taking place.	The amount of carbon emission during computation. Two calculators offered insights into reducing the amount of power needed for computation tasks, such as running an algorithm less time to train it, optimising code to run faster, and choosing data centres powered by renewable energy.	Software developers	To raise awareness of and reduce emissions of computation	8 ● Carbon. FYI ● Carbon Tracker ● Code Carbon ● Eco-conscious Tech Extension ● Green Algorithm ● ML CO2 Impact ● NFT Carbon Cost Explorer ● Tracarbon

[3] We provide numbers for the sake of understanding prevalence within our own cohort, without claiming that such patterns are generalisable to all carbon calculators, i.e. including those that do not meet our specific inclusion criteria.

Carbon Calculator Type	How carbon was calculated for ICT	What information does the calculator provide	Who was expected to use the calculator	Purpose of the calculator	Numbers in our cohort[3] and the examples
Calculation based on the amount of data transfer	The amount of data transferred is firstly inputted and converted from bytes to kWh based on various assumptions about the types of devices used (i.e., smartphones and laptops). This kWh value is then converted into an amount of CO2e based on the geographic location(s) where the power consumption for the data transfer is taking place.	Amount of carbon emissions of a given activity (i.e., internet browsing, visiting a website, streaming video). One calculator provided recommendations for improving the way websites were built as a way to reduce carbon emissions.	Either consumers or developers of services, depending on the purpose of the calculator	Reduce emissions of the activities performed by users	5 • Carbonalyser • Ecograder • Green Web Foundation CO2.js • IEA video streaming emissions • Website Carbon

Carbon Calculator Type	How carbon was calculated for ICT	What information does the calculator provide	Who was expected to use the calculator	Purpose of the calculator	Numbers in our cohort[3] and the examples
Calculation based on the use of a specific service	Data is inputted from multiple sources, such as billing information, amount of time and percentage of equipment used and type of devices used by the service.	Amount of carbon emissions of the service analysed. Calculators providing monitoring dashboards suggested removing idle projects as a way to reduce emissions.	Individuals or organisations that use the services	Monitor carbon emissions of the usage of the service	4 ● Cloud Carbon Footprint ● Google Cloud ● Microsoft Emission Impact Dashboards ● WeNR
Calculations based on the use of digital technologies in everyday life	Users of the calculator input data relating to their general habits of consumption. With ICT questions, including the amount of money they spend on devices and the time spent on services.	Information on the overall carbon footprint. No isolated information on ICT emissions.	Consumers	Calculate the carbon footprint of individuals and households, with two calculators providing evidence for calculating carbon emission offset.	3 ● Carbon Footprint™ ● Ecotree ● SmallWorld Consulting Carbon Calculator

Critique of ICT carbon calculators

In this section, we provide a critique of ICT carbon calculators through the lens of the 'ICT innovation designer'. We adopt a broad definition for design and designer based on the notions proposed by Nelson and Stolterman, "design is a human activity that creates things" (2012) and Bonanni et al., "the choices made in the professional world constitute design" (2010). The designer in our analysis is a professional, making choices about ICT innovation and deciding how digital technologies are created. In this scenario, the designer's aim is to develop digital innovations in a way that minimises negative environmental impacts. We consider what implications there might be if they were to use ICT carbon calculators to support them in their tasks. Reflecting from this designer perspective, we identify three key issues of ICT carbon calculators that currently limit their usefulness to this stakeholder group and look to systemic design for ways to address them.

Hiding complexities

The concept of ICT carbon calculators seems simple—they are tools that assess and output the emissions of a given digital technology or service. However, as explained previously, calculating the emissions of ICT is a complex task. ICT carbon calculators tend to simplify such complexities, making them easier to use and accessible to a greater audience, for example, by hiding the complexities from the graphical user interface and running all the calculations in the background or offering carbon calculations for only the more common situations of ICT use. Instead, ***complexities should be exposed and explained***, for example, by using visualisation tools, such as gigamaps (Sevaldson, 2011). gigamaps could provide support to the designer and stakeholders throughout the innovation process. During their creation, gigamaps lead to a greater understanding of systems and their complexities, and later, they can be used to communicate information that can be layered, enabling zooming in and out of parts of the system.

Another aspect where complexities are hidden is how the calculators hide uncertainties relating to the data, methodologies, and results. This risks users perceiving ICT carbon calculations as straightforward and highly accurate. Decisions regarding the underlying assumptions (i.e., using generic data for calculating the emissions of different types of equipment, estimating the duration of the life of a device, using global averages for energy mix instead of precise location) are also made on behalf of the user. Thus users may not be aware that they could make other choices in configuring calculation parameters or datasets to meet their particular ICT setups or aims. Meadows (2009) also defended exposing assumptions and distributing information in a system. It is important to allow the user agency in decision-making without predetermining their needs through assumptions. This could be achieved by ***making tools interactive*** to enable customisation and ***involving stakeholders in co-design*** to better capture the needs of professionals working in the sector.

Narrow focus

Our typology of calculators (table 1) highlights the fragmentation of ICT carbon calculators, with each taking a narrow view of ICT's environmental impacts. Firstly, ICT carbon calculators are often focused on one specific digital technology or service, calculating the emissions as if they existed at a static point in time and isolated from other activities or forces. Although important in raising individuals' awareness of their own contribution to the problem, this approach does not provide the information needed to understand the carbon emissions within the wider context of the technology or service as an ICT system. Different calculators' results also cannot be aggregated to offer a system-wide view due to the inconsistent methodologies and assumptions taken for each calculator, which could lead either to gaps or to double-counting of emissions.

Secondly, ICT carbon calculators are focused on the use phase of a given digital technology or service, with not enough consideration for the entire ICT lifecycle. Further, they lack consideration of other environmental and social impacts related to ICT, such as (a) the ICT's enablement capacity to reduce emissions in other sectors, (b) the potential rebound effects from developing the ICT, leading to an offset of any emissions savings from enablement or emissions rising overall; and (c) the ethical consequences of the ICT (e.g., the exploitation of people working in mines to extract rare resources for ICT components, or the environmental impact e-waste exported to the developing world, Crawford, 2021). Adopting a systemic perspective would allow carbon emissions of ICT to be perceived within the wider context, ***making results meaningful by presenting multiple views and narratives***. For a designer to make real sustainable change for a given ICT, they need to be able to consider its full system as well as the wider social and environmental systems it is a part of—enabling a complete picture of the structures, activities, practices and innovations that are implicated within ICT's environmental impact. Simply quantifying emissions as numerical CO2 will thus not suffice. Meadows (2009) encourages us to consider not *what is quantifiable* but *what is important* in the system. For example, without being able to accommodate a broader and diverse perspective on the complexities of ICT carbon emissions, a tool doesn't provide insight into possible future carbon emissions rebounds or enablements in different areas occurring from the use of those digital resources.

Post facto calculations

ICT carbon calculators work with data about past activities inputted by users or captured via a tracker associated with their ongoing use of a given digital technology or service. This backwards-looking calculation approach focuses on "what has been" and, thus, the emissions that have already occurred. There is no information on future trends, and there is only limited opportunity for speculation on how emissions will develop in the future. While 13 out of the 20 calculators studied provided an interface where the user could input their own numbers (allowing some measure of planning and exploration of the ICT's emissions), it is important to remember that the underlying assumptions and data sources powering the calculators are still pulling information from past figures. This retrospective view of carbon emissions makes the calculator a tool more suited for a snapshot of current carbon assessment rather than offering a futuristic view of these emissions in line with predicted trends and supporting design decisions for the most sustainable options. This is particularly problematic when it comes to ICT rebound effects, given these occur in the future as a result of, for example, the ICT being deployed or becoming more efficient. What is needed is a way to ***enable experimentation*** to replace linear tools for measurement. This could be achieved through the use of design tools such as ***future scenarios and personas*** to give context and present richer narratives.

Discussion

The research in this paper has been valuable for understanding the landscape around ICT carbon accounting and what is available in terms of tool support for this complex process. There is a degree of sophistication behind these tools, and a lot of research effort has gone into making them more accurate or complete in their estimations. Similarly, there are interesting developments around how to communicate carbon emissions and environmental impacts more generally. Nevertheless, a number of important criticisms have also emerged, particularly around the broader goal of reducing the carbon emissions of the digital sector. It has become clear in researching this paper that while carbon accounting tools have a role to play, their flaws are significant, and they do not help in this broader goal. The lesson to be drawn is, therefore, that we need something else to help with this important and increasingly urgent goal. A broader framework is required, not just a tool, to help with reducing the carbon emissions of technology. Such frameworks should support decision-making at every step through this journey. Whereas tools target the individual, frameworks support the full range of stakeholders involved, including - but far from limited to - the users of technology. This opens the door to broader, more systemic resolutions to reducing carbon emissions and broader environmental (and social) impacts. Here, systemic design can help with its tools for visualising and making sense of complexity, positioned as it is at the intersection of systems thinking and design thinking.

We propose that a framework for responsible innovation focussing on sustainability could help users minimise environmental impacts. Responsible innovation approaches allow us to be prepared for the future, anticipating possible outcomes to build the capacity to deal with uncertain futures (Owen et al., 2013). Responsible Innovation frameworks, such as the AREA framework (Jirotka et al., 2017; Stilgoe et al., 2013), call for anticipation, reflexivity, inclusion and responsiveness in dealing with the potential negative impacts of innovations.

Designing such a framework is fundamentally a transdisciplinary activity, drawing on literature around responsible innovation, design, sustainability and current knowledge of carbon accounting. We can also draw on the critique in this paper to inform such a framework. The conclusions from our analysis point to a design framework that will work simultaneously at abstract and practical levels (Figure 2). It should be guided by responsible innovation principles and offer tools that may support such a framework as part of managing the lifetime of new digital technologies from inception through design to managing the end-of-life of products.

- The first and most important lesson from our findings is that we must bring a systems thinking lens into the nature of the framework (Meadows et al., 2009)—for example, allowing us to look at the big picture and its complexities, appreciating the complex interactions (including enablement and rebounds (Widdicks et al., 2023) in understanding net environmental impacts), understanding the emergent behaviour from complex systems, and allowing stakeholders to zoom in and out of the detail, appreciating the problem at different scales.
- Building on this, it is important not to gloss over the complexities (as carbon calculators do, according to our findings) but rather expose them through principles of openness and transparency—or, more subtly, perhaps translucency (making the right information available to the right people) (Erickson & Kellogg, 2000). This is particularly powerful if it can be combined with agreed or standardised approaches in terms of the data that are necessary to collect and provide and the methodologies for calculating carbon emissions based on this data.
- Given this complexity, it is important not to be too fixated on reducing everything to numbers. Rather, a framework should collect a multitude of evidence, some numerical but some more qualitative, exposing and including the nuances and potential contradictions that may be found around complex systems (cf. wicked problems, Rittel & Webber, 1973).
- Our analysis also shows that a framework can enable the evaluation and comparison of different choices and support consideration of what may happen over time, looking into the possible alternative futures if different decisions were made.

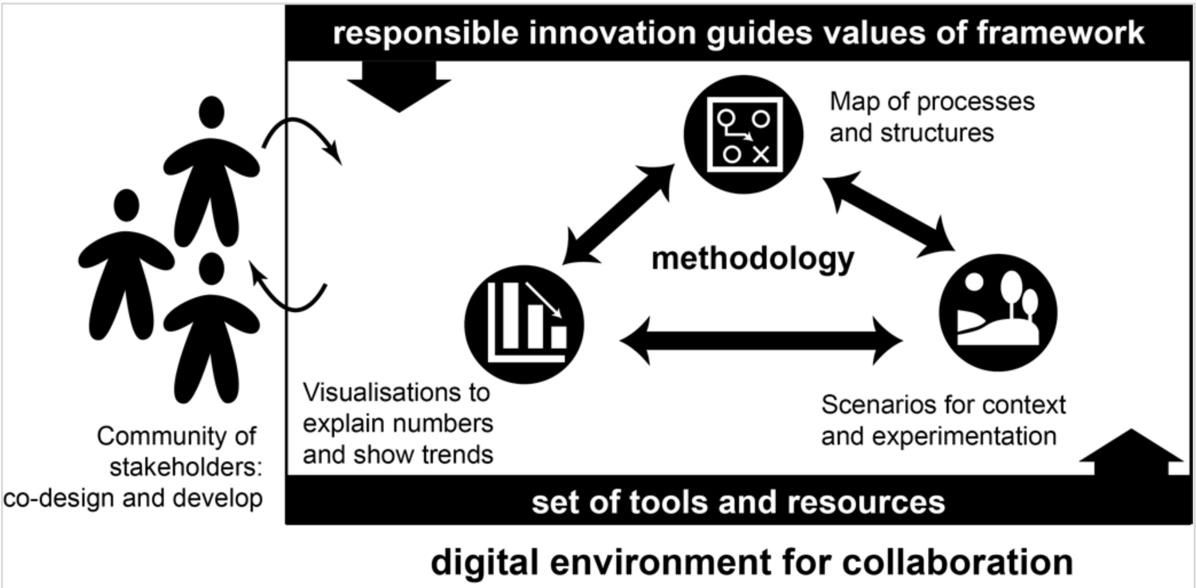

Figure 2: Responsible innovation and systemic design combined in an innovation framework.

Conclusion

We have argued for the need for understanding ICT carbon impacts—not just for any individual ICT product or service being created into the world, but also for ICT as a collective with a (currently growing) carbon footprint. However, our analysis showed that capturing ICT carbon emissions is no simple accounting problem. Reducing ICT's carbon impacts requires that an awareness of these impacts should be embedded in all areas of computing as a design sensibility demanded of today's computing professionals.

This paper is, therefore, a call for research and action to bring systems thinking into the heart of design frameworks and to include experts in systems thinking in shaping developments in this important area. We argue for an approach based on systemic design—providing tools and resources that support understanding the carbon emissions of ICT on different levels of analysis, from different angles or ways of seeing these impacts, in balance with other key sustainability considerations (e.g. social justice and other values-based priorities). Through this systemic perspective, we can tackle the scale and complexity of the problems around significantly reducing the carbon emissions and other environmental impacts of technology in line with international carbon targets, such as those set forth in the Paris Agreement, while also tracking our progress toward this goal. Ultimately, we are calling for the development of a digital sustainability framework that is informed by and reflects an evidence base of ICT's carbon emissions (while recognising their inherent uncertainty and subjectivity) in combination with deliberative, responsible innovation and systemic design approaches to managing multi-level complexity.

References

1. Andrae, A. S. G., & Edler, T. (2015). On Global Electricity Usage of Communication Technology: Trends to 2030. *Challenges, 6*(1), 117-157.
2. Ball, J. (2019). *The Double Diamond: A universally accepted depiction of the design process*. Retrieved 13/06/2023 from https://www.designcouncil.org.uk/our-resources/archive/articles/double-diamond-universally-accepted-depiction-design-process
3. Belkhir, L., & Elmeligi, A. (2018). Assessing ICT global emissions footprint: Trends to 2040 & recommendations. *Journal of Cleaner Production, 177*, 448-463. https://doi.org/https//doi.org/10.1016/j.jclepro.2017.12.239
4. BEREC. (2022). *BEREC Report on Sustainability: Assessing BEREC's contribution to limiting the impact of the digital sector on the environment*. https://www.berec.europa.eu/system/files/2022-07/10282-berec-report-on-sustainability-assessing_0_3.pdf
5. Bonanni, L., Hockenberry, M., Zwarg, D., Csikszentmihalyi, C., & Ishii, H. (2010). Small business applications of sourcemap: a web tool for sustainable design and supply chain transparency. *Conference on Human Factors in Computing Systems, 2*, 937-946. https://doi.org/10.1145/1753326.1753465
6. Buchanan, R. (1992). Wicked Problems in Design Thinking. *Design issues, 8*(2), 5–21. https://doi.org/10.2307/1511637
7. Buchanan, R. (2001). Design Research and the New Learning. *Design issues, 17*(4), 3–23. https://doi.org/10.1162/07479360152681056
8. Checkland, P. (1999). Systems, thinking, systems practice Peter Checkland. *Soft systems methodology: a 30-year retrospective*.

9. Coroamă, V. C., & Mattern, F. (2019). Digital rebound–why digitalization will not redeem us our environmental sins. *Proceedings 6th international conference on ICT for sustainability*. Lappeenranta. http://ceur-ws. org
10. Crawford, K. (2021). T*he Atlas of AI: Power, Politics, and the Planetary Costs of Artificial Intelligence.*
11. Crown. (2022). *Policy paper: Establishing a pro-innovation approach to regulating AI*. https://www.gov.uk/government/publications/establishing-a-pro-innovation-approach-to-regulating-ai/establishing-a-pro-innovation-approach-to-regulating-ai-policy-statement
12. De Vries, A. (2019). Renewable Energy Will Not Solve Bitcoin's Sustainability Problem. *Joule, 3*(4), 893-898. https://doi.org/https://doi.org/10.1016/j.joule.2019.02.007
13. Degot, C., Duranton, S., Frédeau, M., & Hutchinson, R. (2021). *Reduce Carbon and Costs with the Power of AI*. Boston Consulting Group BCG. https://www.bcg.com/publications/2021/ai-to-reduce-carbon-emissions
14. Design Council. (2021). *Beyond Net Zero: A Systemic Design Approach*. Design Council.
15. Erickson, T., & Kellogg, W. (2000). Social translucence: an approach to designing systems that support social processes. *ACM transactions on computer-human interaction, 7*(1), 59–83. https://doi.org/10.1145/344949.345004
16. European Commission. (2021). *Proposal for a regulation of the European Parliament and the Council laying down harmonised rules on Artificial Intelligence (Artificial Intelligence Act) and amending certain Union legislative acts: EUR-Lex-52021PC0206*.
17. European Commission. (2022). *European Green Digital Coalition*. https://digital-strategy.ec.europa.eu/en/policies/european-green-digital-coalition
18. Frayling, C. (1994). Research in Art and Design (Royal College of Art Research Papers, Vol 1, No 1, 1993/4). In. London: Royal College of Art.
19. Freitag, C., Berners-Lee, M., Widdicks, K., Knowles, B., Blair, G. S., & Friday, A. (2021). The real climate and transformative impact of ICT: A critique of estimates, trends, and regulations. *Patterns, 2*(9), 100340. https://doi.org/https://doi.org/10.1016/j.patter.2021.100340
20. Golsby-Smith, T. (1996). Fourth Order Design: A Practical Perspective. *Design issues, 12*(1), 5-25. https://doi.org/10.2307/1511742

21. Gupta, U., Kim, Y. G., Lee, S., Tse, J., Lee, H.-H. S., Wei, G.-Y., . . . Wu, C.-J. (2022). Chasing Carbon: The Elusive Environmental Footprint of Computing. *IEEE MICRO, 42*(4), 37–47. https://doi.org/10.1109/MM.2022.3163226
22. Hsieh, H.F. & Sarah, E. S. (2005). Three Approaches to Qualitative Content Analysis. *Qualitative Health Research, 15*(9), 1277-1288. https://doi.org/10.1177/1049732305276687
23. ITU. (2018). *ITU-T L.1450 (09/2018): Methodologies for the assessment of the environmental impact of the information and communication technology sector* (L series: Environment and ICTs, climate change, e-waste, energy efficiency; construction, installation and protection of cables and other elements of outside plant. L.1400-L.1499: Assessment methodologies of ICTs and CO2 trajectories, Issue. https://www.itu.int/ITU-T/recommendations/rec.aspx?rec=13581⟨=en
24. ITU. (2020, 27 February 2020). *ICT industry to reduce greenhouse gas emissions by 45 per cent by 2030* https://www.itu.int/en/mediacentre/Pages/PR04-2020-ICT-industry-to-reduce-greenhouse-gas-emissions-by-45-percent-by-2030.aspx
25. Jirotka, M., Grimpe, B., Stahl, B., Eden, G., & Hartswood, M. (2017). Responsible research and innovation in the digital age. *Communications of the ACM, 60*(5), 62-68. https://doi.org/10.1145/3064940
26. Knowles, B. (2021). *ACM TechBrief: Computing and Climate Change*. Association for Computing Machinery.
27. Knowles, B., Widdicks, K., Blair, G., Berners-Lee, M., & Friday, A. (2022). Our house is on fire: The climate emergency and computing's responsibility. *Communications of the ACM, 65*(6), 38–40. https://doi.org/10.1145/3503916
28. Malmodin, J., & Lunden, D. (2018). The Energy and Carbon Footprint of the Global ICT and E&M Sectors 2010-2015. *Sustainability (Basel, Switzerland), 10*(9), 3027. https://doi.org/10.3390/su10093027
29. Masson-Delmotte, V., Zhai, P., Pörtner, H.-O., Roberts, D., Skea, J., Shukla, P. R., . . . Pidcock, R. (2018). Global warming of 1.5 C. *An IPCC Special Report on the impacts of global warming of, 1*(5), 43-50.
30. Meadows, D. H., Wright, D., & ProQuest. (2009). Thinking in systems: a primer.

31. Minevich, M. (2022). *How To Fight Climate Change Using AI*. Forbes. https://www.forbes.com/sites/markminevich/2022/07/08/how-to-fight-climate-change-using-ai/?sh=7f80f1462a83
32. Monat, J. P., & Gannon, T. F. (2015). What is systems thinking? A review of selected literature plus recommendations. *American Journal of Systems Science, 4*(1), 11-26.
33. Mortati, M. (2022). New Design Knowledge and the Fifth Order of Design. *Design issues, 38*(4), 21–34. https://doi.org/10.1162/desi_a_00695
34. Nelson, H. G., & Stolterman, E. (2012). The design way: intentional change in an unpredictable world.
35. Owen, R., Stilgoe, J., Macnaghten, P., Gorman, M., Fisher, E., & Guston, D. (2013). A Framework for Responsible Innovation. 27–50. https://doi.org/10.1002/9781118551424.ch2
36. Pohl, J., Hilty, L. M., & Finkbeiner, M. (2019). How LCA contributes to the environmental assessment of higher order effects of ICT application: A review of different approaches. *Journal of cleaner production, 219*, 698-712. https://doi.org/10.1016/j.jclepro.2019.02.018
37. Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a General Theory of Planning. *Policy sciences, 4*(2), 155-169. https://doi.org/10.1007/BF01405730
38. Schwartz, R., Dodge, J., Smith, N. A., & Etzioni, O. (2020). Green AI. *Communications of the ACM, 63*(12), 54–63. https://doi.org/10.1145/3381831
39. Sevaldson, B. (2011). GIGA-Mapping: Visualisation for complexity and systems thinking in design. *Nordes*(4).
40. Sevaldson, B. (2017). Redesigning Systems Thinking. *Formakademisk, 10*(1). https://doi.org/10.7577/formakademisk.1755
41. Stilgoe, J., Owen, R., & Macnaghten, P. (2013). Developing a framework for responsible innovation. *Research Policy, 42*(9), 1568-1580. https://doi.org/https://doi.org/10.1016/j.respol.2013.05.008
42. Stoll, C., Klaaßen, L., & Gallersdörfer, U. (2019). The Carbon Footprint of Bitcoin. *Joule, 3*(7), 1647-1661. https://doi.org/https://doi.org/10.1016/j.joule.2019.05.012
43. Sweeting, B., & Sutherland, S. (2022, October 3–16, 2022). Possibilities and Practices of Systemic Design: Questions for the next decade of Relating Systems Thinking and Design. *Relating Systems Thinking and Design, RSD12.* https://rsdsymposium.org/questions-for-systemic-design/

44. Widdicks, K., Lucivero, F., Samuel, G., Croxatto, L. S., Smith, M. T., Holter, C. T., . . . Penzenstadler, B. (2023). Systems thinking and efficiency under emissions constraints: Addressing rebound effects in digital innovation and policy. *Patterns (N Y), 4*(2), 100679-100679. https://doi.org/10.1016/j.patter.2023.100679
45. Williams, E. (2011). Environmental effects of information and communications technologies. *Nature, 479*(7373), 354–358. https://doi.org/10.1038/nature10682

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Appendix

The 20 ICT Carbon Calculators analysed

name	type	device, function or activity measured	Summary and link to the calculator
Carbon Footprint ™	part of lifestyle	includes devices and services	Calculation is based on the amount of money spent on an individual's lifestyle. For ICT, equipment, and services i.e., TV, mobile phone. Results are the total carbon emission of that person, visualised as a footprint and compared with the country and world averages. Available to the public and invites the user to care for the world and communities by carbon offsetting. *https://www.carbonfootprint.com/calculator.aspx*
Carbon. fyi	power consumption	Ethereum	Web page where the users of cryptocurrency Ethereum enter an Ethereum address to calculate their emissions. Calculations based on 'gas' used and hash rates provided by Ethereum. Promote offsetting emissions. *https://carbon.fyi/://www.carbonfootprint.com/calculator.aspx*
Carbon tracker	power consumption	training deep learning models	Users install and run code to capture the emissions of the training model. For developers to be aware of their carbon emissions and take action to reduce them. Provides comparison to km travelled by car. *https://github.com/lfwa/carbontracker*
Carbonalyser	data transfer	Internet browsing traffic	Tracker (add-on) for browser and app for internet users. Based on 1byte methodology with the intention to raise awareness of the impact of digital technologies. Provides an interface with visualisations and comparisons to charging a smartphone and driving a car. *https://github.com/carbonalyser/Carbonalyser*

name	type	device, function or activity measured	Summary and link to the calculator
Cloud Carbon Footprint	service use	using a cloud computing service	Calculator for users of cloud computing to find out the carbon emissions of their cloud services use (include Azure, Google, and AWS). Aims to show how cloud usage impacts the environment. The methodology builds on Cloud Jewels. Compares the result to flights, mobile phone charging and growing trees. *https://www.cloudcarbonfootprint.org*
Code Carbon	power consumption	energy used in compute	Code that enables developers to track the emissions of their work. Calculation is based on power consumed multiplied by the carbon intensity of the location of the energy used. Created for developers in response to the increasing energy usage of ML. Compares results to emissions of average weekly household energy consumption, driving a car and time watching LCD TV. *https://mlco2.github.io/codecarbon/index.html*
Ecoconscious tech extension	power consumption	power spent working on a project	Calculates and displays estimated cumulative carbon emissions on the toolbar. Calculation based on capturing energy usage multiplied by location energy mix factor based on IP address. To raise awareness of environmental impacts. *https://github.com/catherinedparnell/ecoconscious-tech-vsc*
Ecograder	data transfer	website (webpage)	Calculate the emissions of a website based on the web address. Providers a score for how sustainable the website is along with carbon emissions based on a certain number of visits to the page in a month. Check if the site is hosted with renewable energy. Provides advice on how to make the site more sustainable. *https://ecograder.com*

name	type	device, function or activity measured	Summary and link to the calculator
Ecotree	part of lifestyle	internet use (separate entries for video streaming and browsing)	Provides a calculation based on a person's consumption habit. In relation to ICT, it asks for data on the internet and video streaming use. Not aimed at any specific groups. Calculation to illustrate emissions that could be offset by using their service. *https://ecotree.green/en/calculate-digital-co2*
Google Cloud	service use	Google Cloud services	Provide carbon emissions calculations for users of Google Cloud services aiming to report and reduce emissions. The methodology is developed in-house and reviewed by a third party. Provides a dashboard with visualisations and makes suggestions to remove idle projects to reduce emissions. *https://cloud.google.com/carbon-footprint*
Green Algorithm	power consumption	carbon emissions of compute	Calculates the emissions of running an algorithm. Provides a dashboard where user can enter detailed information about their equipment and duration and location where computation takes place. Provides information and comparisons to tree sequestration, distance travelled by car and flights. *http://calculator.green-algorithms.org*

name	type	device, function or activity measured	Summary and link to the calculator
Green Web Foundation CO2.js	data transfer	emissions of data transfer	Tool for developers to calculate carbon emissions of data being transfer over the internet considering the location and if the website is hosted by a green web host. Combines 1byte and Sustainable Web Design methodologies. Aims to expose emissions of digital activities to benefit developers and end-users. *https://www.thegreenwebfoundation.org/news/startcalculating-digital-carbon-emissions-in-5-minutes-with-co2-js/*
iea Video Streaming emissions	data transfer	video streaming	This calculator is part of a blog contesting previous research on calculating carbon emissions of video streaming. Reviews 1byte methodology and adds more streaming devices to the calculations. Presents results with visualisations and comparison to the emissions of boiling a kettle. *https://www.iea.org/commentaries/the-carbonfootprint-of-streaming-video-fact-checking-the-headlines*
Microsoft emissions impact dashboards	service use	cloud computing services use	Carbon emission calculations for users of Microsoft cloud services (including Azure and 365). Provide dashboard with visualisations on the user/account cloud usage and carbon emissions. Methodology developed in house and reviewed by third party. To be used to report emissions and inform users. *https://www.microsoft.com/en-gb/sustainability/emissions-impact-dashboard*

name	**type**	**device, function or activity measured**	**Summary and link to the calculator**
ML C02 Impact	power consumption	Machine learning algorithm	Carbon calculator to estimate the emissions of running algorithms for Machine Learning for research. Calculations based on hardware use, cloud provider information and amount of runtime. Produce the results of carbon emissions produced and reports if cloud providers have already offset the emissions. Comparisons to cars, coal burning and tree sequestration. *https://mlco2.github.io/impact/*
NFT Carbon Cost Explorer - Project O.N.C.E.	power consumption	NFT (Ethereum)	Demo of a calculator for blockchain carbon emissions broken down to the transaction level. Uses data from Ethereum but allows users to select different functions (mining, transaction, etc.). Calculation based on 'gas' cost and energy mix. Emissions compared to cars and trees. *https://github.com/operation-nifty-carbon-emissions/nft-carboncost-visualizer*
Small World Consulting Carbon Calculator	part of lifestyle	gadgets and appliances (groups ICT devices with other appliances)	calculates emissions of an individual based on expenditure on services and products. In relation to ICT includes expenses with gadgets and appliances (smartphones, laptops and TVs) and other bought services (including internet). Provides visualisation and comparisons to country averages and UK targets for 2050. *https://www.sw-consulting.co.uk/carbon-calculator*

name	type	device, function or activity measured	Summary and link to the calculator
Tracarbon	power consumption	device energy consumption	For developers to install and run code to capture the energy consumption of a device and translate it into carbon emission based on location. Also, account for Cloud providers' emissions using data from the Cloud Carbon Footprint calculator. *https://github.com/fvaleye/tracarbon*
Website carbon	data transfer	website (webpage)	Calculates emissions based on the web address provided by the user (based on the homepage). Methodology based on Sustainable Web Design. For internet users, web designers and developers. To raise awareness and for "a more sustainable internet". Provide comparison to the weights of sumo wrestlers, emissions of bubbles, trees and electric cars. *https://www.websitecarbon.com*
WeNR	service use	information services	Calculates the emissions of the information systems of an organisation. Users download forms online, fill and submit them for calculation. Requests for very detailed information probably need to be filled in by different functions inside an organisation. Results are provided back to users as a report, and they can see how they fare against other local organisations. Combine assessment, audit, and the ability to set some targets for future assessment. Based on the methodology described in ITU.1450 recommendation. *https://wenr.isit-europe.org.*