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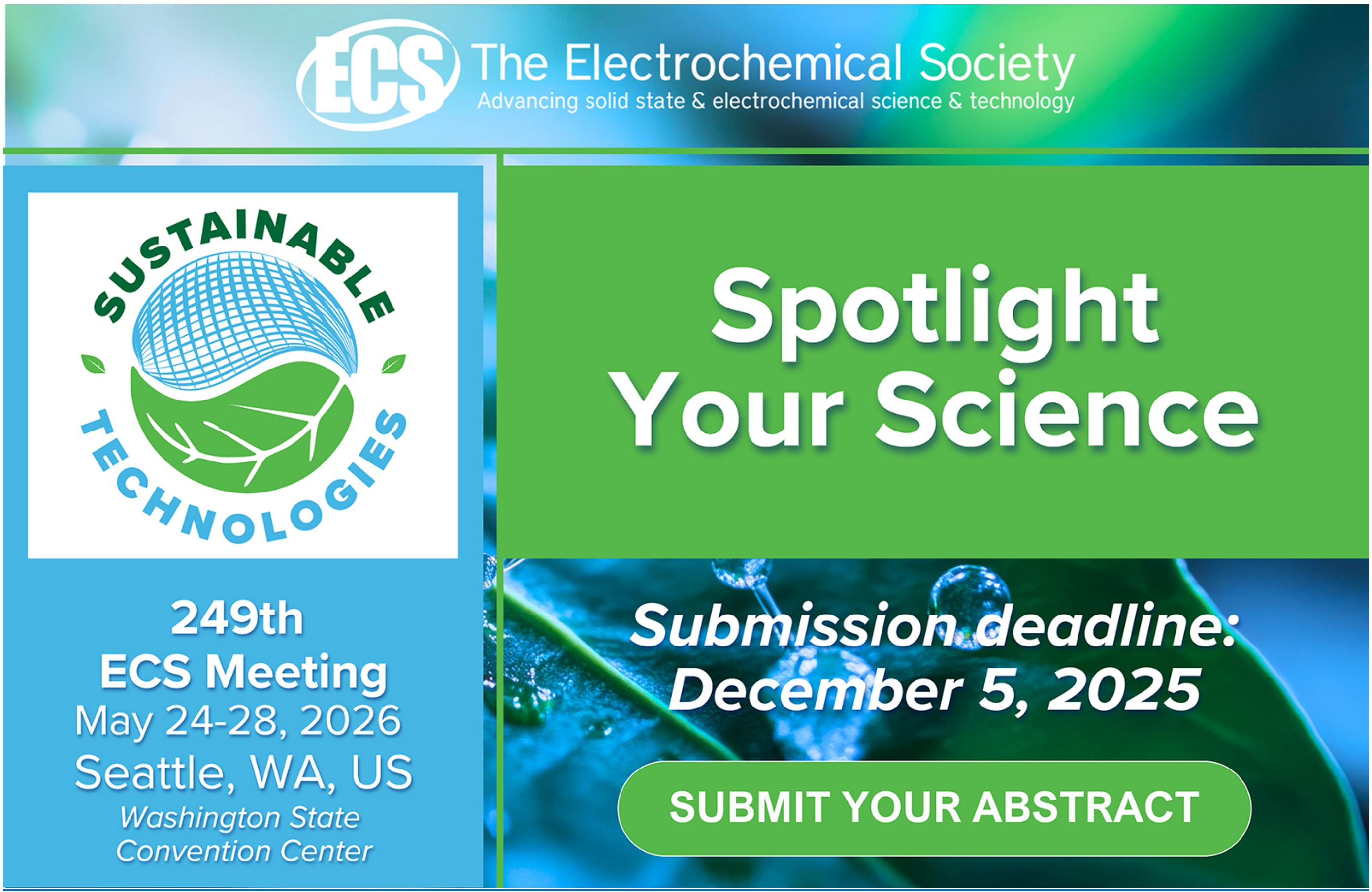

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Climate impacts of digital use supply chains

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Abstract

Information and communications technology (ICT) has become an indispensable part of our lives. Prior research on climate impact of ICT devices and services mostly makes use of life cycle assessment and energy modeling frameworks focused on embodied greenhouse gas (GHG) emissions. Because these perspectives emphasize the GHGs emissions associated with the construction and distribution of digital devices along production supply chains, not much is known about the GHGs emissions monitored or facilitated by digital device use. In this study, we propose the concept of digital use supply chains (DUSCs) as an orthogonal dimension of digital devices' life cycle. DUSC refers to the production activities and resource consumption recorded by digital devices. We propose a framework to conceptualize and quantify digital behavior-related GHGs emissions through use of the Screenomics paradigm, where users' digital screen data are unobtrusively collected moment-by-moment. Through Screenomics' granular recording of users' digital behavior, we evaluate behavior-based GHGs emissions traced by the digital devices. DUSC connects individual's digital behaviors to their global climate change impact, contributing to a more nuanced and complete evaluation of the climate impacts of the digital economy. Our single-case study indicates the estimated scale of the GHGs emissions linked to a user's one-day digital activities could be three orders of magnitude (1000 times) higher than the emissions associated with the device life cycle alone. DUSC could enable climate change mitigation at a meaningful, actionable level through personalized educational or behavior change programs, and also facilitate novel data-driven feedback loops that may provide digital device users with insights into their personal climate impacts. Recognition and future study of DUSC could accelerate the quantification and standardization of a 'carbon handprint' of digital devices and create positive climate impacts from digital products and services.

1. Introduction

Much of life is now lived on and through digital devices. All over the world, people spend many hours of their day using their information and communications technology (ICT) devices to engage with work, school, entertainment, relationships, travel, food, health, politics, purchases and much more (Reeves *et al*

2019). The breadth of personal digital activities, and the increasing number of hours spent on digital devices everyday, has substantial environmental consequences. ICT devices, the network and computing infrastructures that connect those devices to content, and the electricity used to power these devices all contribute to greenhouse gas (GHG) emissions that have substantial climate impact. As of 2018, the life cycle GHGs emissions of the ICT industry, including the raw material extraction, manufacturing, transportation, use, and end-of-life impacts, likely already reached above 1000 million metric tons (MMT) CO2e in 2018, and comprises approximately 3%–5% of global GHG emissions (Belkhir and Elmeligi 2018, Malmodin and Lundén 2018). In this study, we suggest that the GHGs emissions tied to the use of ICT devices is higher and more consequential than the device embedded GHGs emissions. Furthermore, these costs are not properly baselined in current GHGs accounting schemes.

In current digital device GHGs accounting practices based on life cycle assessment (LCA) framework, the use phase GHGs emissions of digital devices are typically computed by summing the device's energy consumption under different use scenarios (e.g. in sleep mode, in transmission mode) and multiplying by regionalized grid emissions factors (Shi *et al* 2022, Suckling and Lee 2015). This approach, however, only accounts for device energy consumption and does not consider the many high carbon intensity activities—such as traveling and purchasing—that are linked to device use. With a few swipes, ride shares travel multiple miles to a pick-up location; a few more button presses, and food is transported from a warehouse to a doorstep. The current approach for calculating use phase GHG emissions for ICT devices excludes these types of activities because they are considered to be outside the system boundaries (Suckling and Lee 2015). Restricting the system boundary to the physical device makes sense from the perspective of GHGs reporting by ICT device producers or suppliers whose GHGs mitigation levers are primarily alternatives in materials, manufacturing technologies, or energy sources. However, this restriction overlooks the capability of ICT devices to provide insights about sustainability consequences of individual's digital behavior within the broader supply chains. Including digital device use as part of the system might further enable discovery of creative decarbonization solutions for the rapidly developing world of an internet of things (Hittinger and Jaramillo 2019).

Prior studies have discussed the positive and negative environmental ramifications posed by ICT devices. Coroamă *et al* reviewed existing methodologies and proposed how the efficiency improvements as well as rebound effects for ICT use could be quantified (Coroamă *et al* 2020). Subsequently, the International Telecommunication Union (ITU) provided recommendations for how CO_2 trajectories related to ICTs might be included in technology-oriented and company-level reporting (ITU 2022). Multiple industry-led reports have expressed optimism about ICT's role in creating a more resource efficient future, particularly through displacement of work-related commuting via video conference (Carbon Trust 2021, GSMA 2019). At the same time, there are concerns about rebound effects and calls for careful alignment when claims are made about avoided emissions (Håkansson and Finnveden 2015, Mission Innovation 2020).

Despite these meaningful discussions, detailed knowledge about the GHGs emissions resulting from digital device use is still lacking, in part because comprehensive and accurate accounting of the climate change impacts is complex. That accounting requires tracking of both (1) the energy and resources digital devices are consuming, and (2) the energy and resources that the user is consuming via actions mediated or induced by their digital devices. Current method for calculating (1) are often imprecise and based on broad and unsubstantiated assumptions about individuals' actual device use (Suckling and Lee 2015). Current methods for (2) only consider device energy use of specific users. The GHGs emissions associated with a user's digital behavior is considered outside of the scope of a standard device LCA (Belkhir and Elmeligi 2018). Therefore, we propose a new measurement and accounting framework with expanded system boundary compared to current methods in this paper. This approach enlarges the system perspective on a digital user's *use phase* GHGs emissions by pushing the system boundaries well beyond the device and hardware related energy consumption and considering impacts of digital behavior.

In this study, we forward a new concept called digital use supply chains (DUSCs). A supply chain is traditionally defined as 'the activities and infrastructure whose purpose is to move products from where they are produced to where they are consumed' (Snyder and Shen 2011). Aligning this definition with modern digital life, we define DUSC as the activities, resources, and infrastructure that enable scenarios of digital device use. As such, DUSC includes the energy and resources required to power both the device and the actions mediated or induced by the device. We illustrate here how new tools developed for comprehensive study of individuals' everyday digital lives—i.e. Screenomics—can facilitate temporally precise tracking of DUSC. In the following sections we review current methods employed in device LCA, and outline a process-based economic input–output (EIO) approach that leverages screenomics and existing life-cycle inventory data to calculate a comprehensive device, infrastructure, and behavioral GHGs impacts for individual users. We then illustrate how DUSC analysis proceeds in practice through a case study. In closing, we highlight the possibilities for engaging analysis of DUSC analysis at scale and how this new approach can contribute to sustainability research and practice.

2. Method

2.1. Screenomics paradigm

Our device digital use data is collected via the Screenomics paradigm. Comprehensive observation and analysis of everyday ICT device use is notably difficult because the devices are mobile, used broadly in a variety of contexts, and used idiosyncratically, often in short spurts. People turn on their smartphones hundreds of times per day to engage in sessions that most often last less than 15 s (Brinberg *et al* 2021). Recently, the Screenomics Lab at Stanford University has developed and deployed a data collection and analysis framework that opens for inquiry the full record of individuals' *in-situ* digital behaviors, tracking moment-by-moment changes as they engage with different applications, platforms, and commercial products (Reeves *et al* 2019). In brief, study participants download software onto their smartphones and laptops that unobtrusively takes screenshots every 5 s when the device is in use, encrypts and transfers those screenshots (along with associated metadata) to secured, privacy protected and HIPAA compliant research servers. The resulting sequences of screenshots provide comprehensive records of device use that can be parsed, evaluated, and used to study all aspects of digital life (Ram *et al* 2020, Reeves *et al* 2020). Leveraging advances in computer vision, optical character recognition, natural language processing, and the possibility to apply new forms of artificial intelligence on streaming data, screenome data are 'assayed' to obtain feature sets that describe changes in screen content (Chiatti *et al* 2017, Reeves *et al* 2019). Thus far, these feature sets have mostly been used to infer and study users' engagement with specific kinds of applications (e.g. social media, web-browsing), and the psychological states (e.g. emotions, cognitions) that motivate and follow from the graphical and textual content encountered in digital life (Reeves *et al* 2019). In this paper, we illustrate a new use case of the Screenomics paradigm: facilitating DUSC analysis to inform on digital devices users' climate change impact.

2.2. Functionality-based life cycle assessment (FLCA)

Our device GHGs impact assessment approach follows the FLCA approach. In conventional LCA of digital devices as illustrated in figure 1, Panel (a), the assessment includes the raw materials and energy impact associated with manufacturing, transporting, use, and end-of-life processing of the device. Generally, the use phase impact is calculated as the average energy consumption drawn by the devices based on an average user's energy consumption of the device during an assumed estimated lifetime. This approach considers the impact of transmission and network infrastructure invoked by the device as out of scope. And most importantly for this proposal, current device LCAs consider the materials and energy impact associated with users' digital behaviors beyond device energy consumption out of the scope as well (Judl *et al* 2012). These gaps are acknowledged by the academic community via analysis that highlights the increasing environmental impact of the infrastructure required to generate and transmit information to/from digital devices (Malmodin and Lundén 2018, Masanet *et al* 2020). In addition, recent research has explored a functionality-based impact assessment method (FLCA) for ICT devices that reveals these previously hidden impacts to obtain more comprehensive and accurate quantifications of the environmental impacts of digital devices (Suckling and Lee 2015, Shi *et al* 2022).

In our study, we use the FLCA framework and provide an in-depth understanding of digital devices' sustainability impact during device use. Specifically, as shown in Panel (b) of figure 1, we consider the DUSC as the activities, resources, and infrastructure required to enable the full range of use scenarios associated with a digital device. For example, when the device is idling, it is drawing energy from the power supply. When the device is used to watch a video, it is using the battery to power up the device as well as utilizing the Internet to receive the video streaming. When the device is used to order takeout food, it is communicating with food provider to place the order. Each scenario relates to different energy and resource requirements.

Theoretically, the end-point impact metric for the full use supply chain of a digital device can be any sustainability metric of interest, including, for example, GHGs, water, and land use etc. Focusing on the important issue of climate change, we mainly consider GHGs emissions as the evaluation metric in this study (O'Neill *et al* 2015). Following the functionality-based LCA approach, we can conceptualize GHGs emissions impacts at three levels: (1) device level—the GHGs generated from drawing electricity from a source to power the device; (2) infrastructure level—the GHGs generated from drawing electricity to power the infrastructure that enables the device use, including data centers, wirelines, and network equipment; (3) behavioral level—the GHGs generated from the specific actions invoked by the device user, including transportation and online shopping (Shi *et al* 2022). We propose and illustrate an analytical framework to quantify the GHGs impact of the use supply chain using data collected at the digital device level as well as

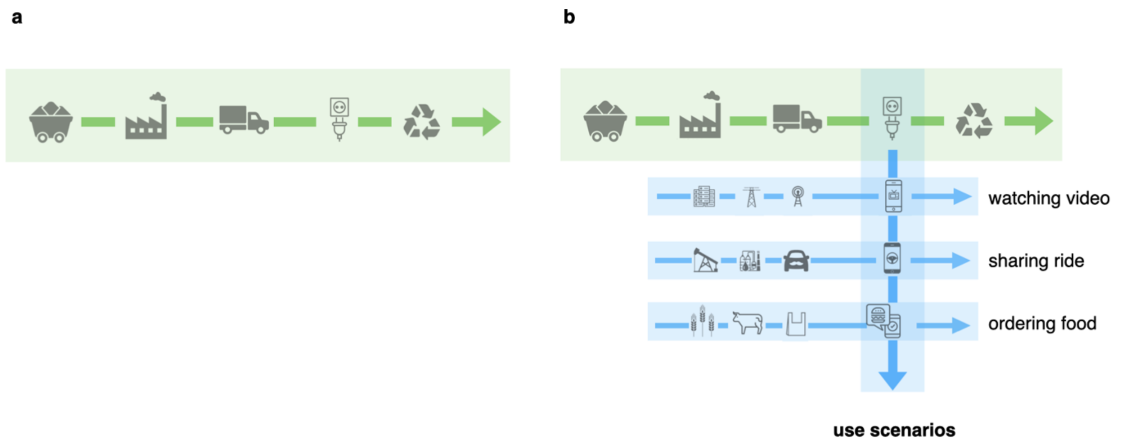

Figure 1. Conceptual representation of digital use supply chains. Panel (a) shows conventional life cycle assessment analysis scope. Panel (b) shows use supply chain analysis scope. The green arrows refer to the standard life cycle phases of a digital product; the blue arrows refer to the multiplicity of use for a digital device such as a smartphone as well as the corresponding production activities related to the specific use scenario.

other administrative data to infer and estimate the total amount of GHGs generated by an individual user on one day.

Following the FLCA method, the environmental impact of DUSC can be described using the equation below. Different from conventional manufacturing supply chain, this view only considers user-specific environmental impacts from interaction with digital devices,

$$G_{\text{digital use supply chain}} = G_{\text{device}} + G_{\text{infrastructure}} + G_{\text{behavior}}$$

where the three components can be described as below. G denotes the environmental impact in unit of gram or kilogram CO2e; P denotes power consumption in unit of watt; T denotes time in unit of hour; and ef denotes emissions factor in unit of CO2e per unit energy or resource consumption,

$$G_{\text{device}} = \left(\int_0^T P_{\text{cpu}}(t)\,\mathrm{d}t + \int_0^T P_{\text{network}}(t)\,\mathrm{d}t \right) \times ef_{\text{device\_specific}}$$

$$G_{\text{infrastructure}} = \left(\int_0^T P_{\text{base\_station}}(t)\,\mathrm{d}t + \int_0^T P_{\text{wireline}}(t)\,\mathrm{d}t + \int_0^T P_{\text{data\_center}}(t)\,\mathrm{d}t \right) \times ef_{\text{infrastructure\_specific}}$$

$$G_{\text{behavior}} = \sum_{i=1}^{N} G_i = G_{\text{transport}} + G_{\text{food}} + G_{\text{purchase\_commodity}} + \ldots + G_{\text{behavior\_}N}$$

2.3. Single-case study

We use a single-case study design for our analysis. Single-case design is usually appropriate when the case represents a critical case to serve as a test (Darke and Shanks 2002). It allows researchers to investigate a phenomenon in-depth with rich description and understanding. It also applies when conducting a pilot study where the study is exploratory in nature. The benefit of the pilot study is to build and refine data collection and analysis procedure. Due to the nascent nature of digital sustainability behavior, we proceed with a single-case study design with the primary goal to share our analysis procedure and receive feedback to further scale up.

2.4. Analysis process and calculation steps

Our analytical process has three main components of the workflow as illustrated in figure 2. First, we comprehensively observe, via measurement of the screenome, device users' digital behaviors *in situ*—as they occur naturally in everyday life. Second, the screenome data are used to identify and describe users' specific activities. Third, the activity time-series are combined with existing databases and knowledge of the energy costs associated with these activities to estimate the GHG emissions associated with users' digital activities.

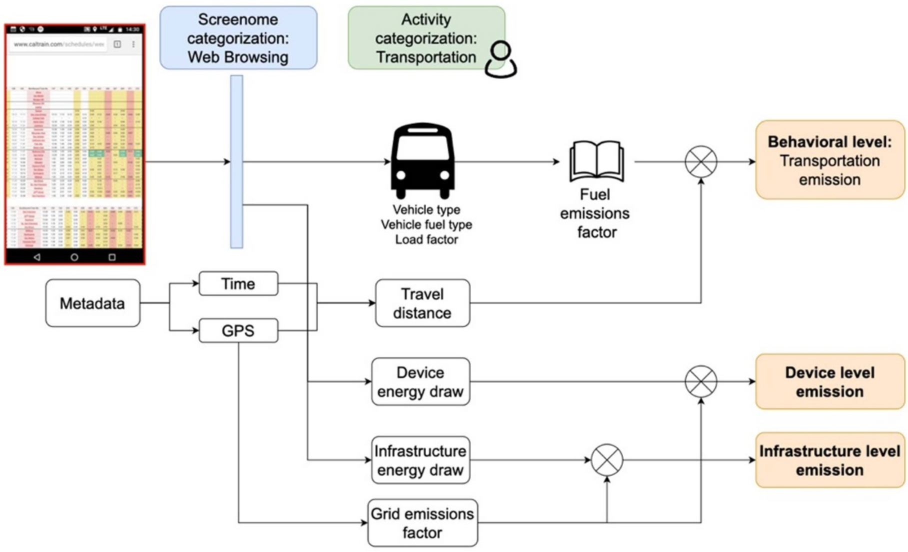

Figure 2. Example of an analysis flow of digital use supply chain. The diagram illustrates the analysis flow of the DUSC. At the very left of the diagram is a screenshot from a digital device (metadata). The screenshot data are then characterized and complimented by time and location-based data from the research team. Finally, a researcher calculates the GHGs emissions at the device, infrastructure, and behavioral level based on administrative data (e.g. vehicle details) and literature review (e.g. grid and fuel emissions factors).

First, the metadata of digital device users' behavior are collected. Here, we use the Screenomics data and processing pipeline to derive the broad environmental impact of the DUSC. We obtained exemplary Screenomics data obtained from a young adult volunteer as they used a pair of ICT devices (smartphone and laptop)—*in situ*—during 24 h of regular daily life. The data include morning wake-up to an alarm, preparation for and participation in school activities, running an online cosmetics resale business, interacting with friends and family, shopping online, arranging travel, coordinating meetings, and so on. These digital activities can then be linked to relevant energy and resources consumption.

Second, the screenome data were used to identify and describe user activities. Extraction of features relevant for sustainability research is done using a taxonomy and a categorization procedure that identifies types of user behavior that can be paired with existing data about the energy, resource consumption, and environmental impact of each behavior. Using the behavioral taxonomy shown in figures 3 and 4, each smartphone screenshot in the screenome sequence was classified as indicating user engagement in 1 of 14 types of smartphone activities, each linked to energy and resource consumption. In parallel, each laptop screenshot was classified as indicating user engagement in 1 of 9 types of laptop activities. Using this taxonomy and procedure—which can be both automated and iteratively updated with additional behaviors as they emerge—the screenome for the full 24 h period is recast as a detailed activity diary. In our initial case study, the dominant activities observed during each minute were labeled and categorized using the taxonomy. When there are multiple activities in one minute, the researcher identifies one dominant use case based on the most frequent or the most energy consuming activity during that minute. Due to privacy protection, specific commercial transaction data are masked in the screenshots. Therefore, the researcher is only able to identify the highly likely cases for product consumption based on product page view. For transport activities, the researcher combines the screenshot data as well as the location information via GPS data to identify the modes of travel as well as the distance travelled on a per-minute basis.

Third, as described in detail in the next section, the activity time-series is combined with existing databases (see supplementary information) to specifically calculate the energy costs associated with each digital activity (i.e. the use scenarios in figure 1). For each activity, we specifically evaluate and consider the energy costs associated with the (1) device, (2) infrastructure, and (3) behavior itself.

To calculate the energy and GHGs emissions associated with the user activities, we first estimate the energy and resource consumption and then apply a conversion factor (also referred to as emissions factor, or *ef*) to calculate the corresponding GHGs emissions in the form of grams CO_2e. To capture the life cycle environmental impact at these levels, we use a hybrid LCA approach. In a typical product-level LCA, process-based LCA is preferred due to its specificity in modeling the product and manufacturing processes. However, due to constraints in data availability, process-based LCA cannot cover a wide range of consumer products and services. Therefore, we complement the process-based LCA with EIO-LCA. The EIO-LCA database estimates the GHG emissions of spending on categories of commodities based on macro-economic data. For example, one dollar spent on cosmetics results in approximately 700 g CO_2e, and one dollar of food purchases equals approximately 1000 g CO_2e emissions.

The GHGs emissions of the DUSCs is then calculated for the three levels—device, infrastructure, and behaviors. For digital devices, the device level impact refers to the GHGs emissions generated from drawing electricity from a source to power the digital device. The infrastructure impact refers to the GHG emissions of power draw from wirelines, network equipment, and data centers. For example, digital devices' energy consumption can be estimated based on the device activity type in literature (Yan *et al* 2019). Laptop power draw ranges from 4 W to 15 W at the device level and 10 to 40 W at the infrastructure level. Smartphone power draw ranges from 0.4 W to 0.5 W at the device level using an existing study with Galaxy Note 3 as a proxy and 0.1 W to 0.7 W at the infrastructure level assuming 4G network is in use (Yan *et al* 2019).

The behavioral level refers to the embedded energy and resource GHGs impacts from user activities such as purchasing and movements. The user activities captured by the Screenomics paradigm contain a variety of consumption activities that are difficult to specify in the LCA. Therefore, we used an EIO-LCA approach and estimated the GHGs emissions of these consumption activities based on the economic value of the product or services that are involved. To calculate the GHG emissions of the consumption activities, we use life cycle inventory data from the Carnegie Mellon EIO-LCA database (Carnegie Mellon University Green Design Institute 2008). We use fuel emissions data from the Center for Sustainability Accounting to calculate the GHG emissions of various mobility options. The key assumptions during this calculation are reported in the supplementary information.

2.5. Allocation

One key complexity of the GHGs emissions calculation is the allocation of environmental consequences. Therefore, we followed an allocation process for the behavioral GHGs impact calculations that ensured accurate accounting of individual-based versus shared-resource behaviors. Note that for the device and infrastructure level GHGs impact calculation, no additional allocation is required because the baseline data are already collected at the individual device level. For the behavior level impact, the user might engage in shared-resource activities, such as public transit or a group meal. As part of the analysis process, we ensure that when the user is participating in a shared resource activity, their GHGs impact is allocated based on the estimated number of shared participants of the resource. For example, we allocate passenger specific GHGs emissions when the participant takes public transportation. In the initial analysis, we do not consider any displacement or any credit that could be taken via using shared resource behaviors. We discuss the implication of displacement or credit taking in the discussion section.

3. Results

3.1. The GHG impact of DUSC in a day's time

We illustrate a DUSC analysis of a young adult volunteer using Screenomics data obtained during a 24 h period (wake-up to wake-up). Smartphone and laptop screenshots were collected at 5 seconds intervals whenever the volunteer was using their smartphone and/or laptop, and then screens were encrypted and transferred to a secure research server for later analysis. In our example, the total time that one or both devices were in use was 368 min (6.1 h); 26% of the total 24 h observation period. The screen activity time-series was derived using the taxonomy developed by the research team. As shown in figures 3 and 4, the laptop was mostly used for web browsing and typing, and the smartphone was used for a wide array of activities and was often idle.

The minute-by-minute GHG emissions associated with each activity—device, infrastructure, and behavior—were then calculated as described above. Results are shown in figure 5 (log scale). Device emissions shown in orange, infrastructure emissions are shown in yellow, and behavioral emissions are shown in green. Immediately noticeable in the figure is how the behavioral level dominates the DSUC GHG emissions.

Device-level GHGs emissions refers to the GHGs impact of direct (local) energy used by device hardware, and is relatively insignificant compared to other activities. To calculate the GHG emissions for device energy use, we used the California demand side emissions factor 0.23 kgCO2e/kWh because the person generating the screens is based in California (de Chalendar *et al* 2019). Total device-level GHGs was 0.01 kgCO2e during the one-day period.

Infrastructure-level GHGs emissions refers to the GHGs impact of remote energy use for the supporting infrastructure such as networks and data centers. In figure 5, the spikes in the middle of the day as well as after midnight are generated by online video watching on YouTube and Netflix. Total infrastructure-level GHGs was 0.02 kgCO2e.

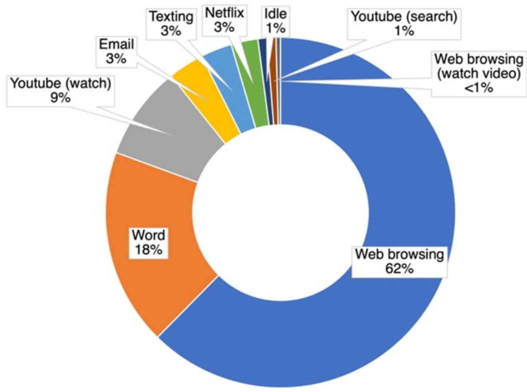

Figure 3. Laptop use time breakdown of the volunteer in a day when display is on.

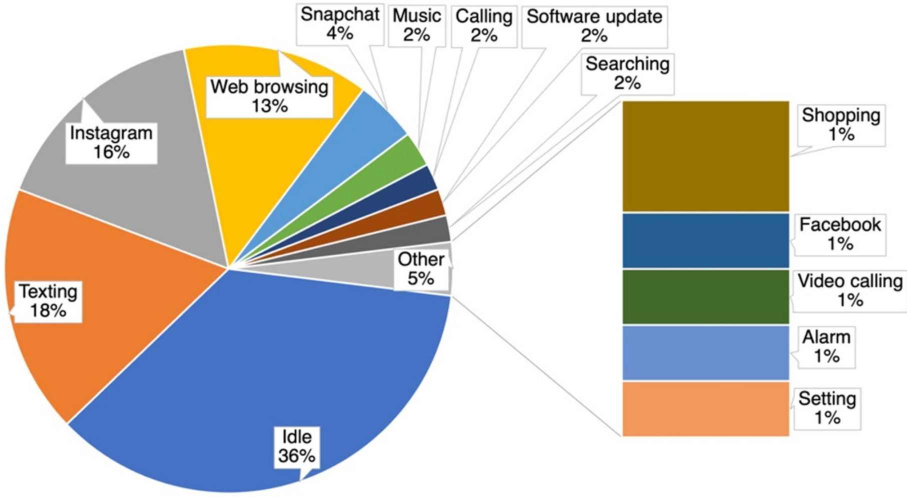

Figure 4. Smartphone use time breakdown of the volunteer in a day when display is on.

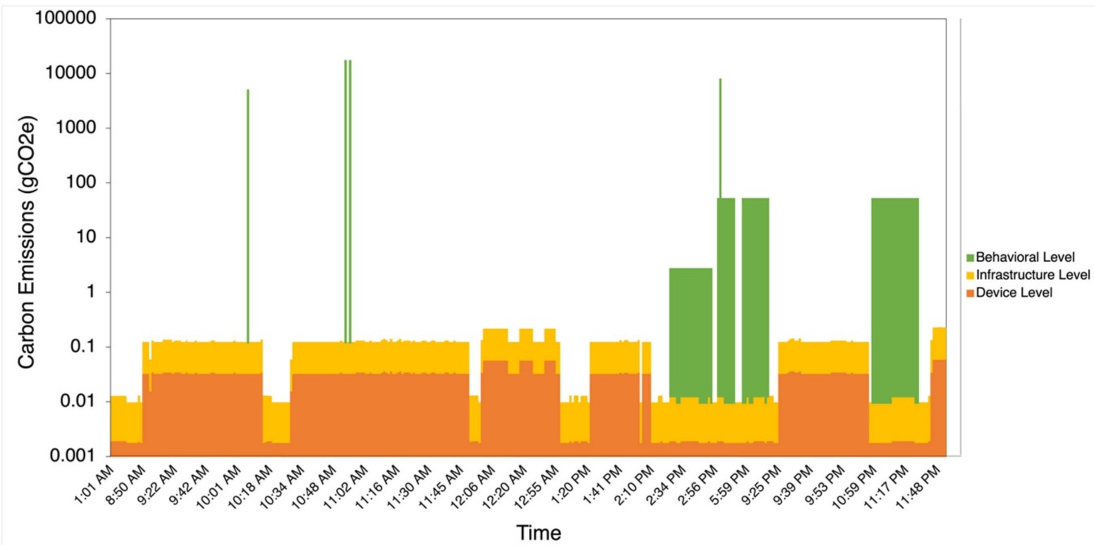

Figure 5. Estimation of an individual's one-day digital use supply chain using Screenomics data (plotted in logarithmic scale).

Behavior-level GHGs emissions result from device-enabled engagement with transport and purchases of retail products and food. The morning spikes are incurred from a round-trip journey by bus and train. We used California's electric bus's average emissions factor allocated per passenger based on the estimated number of seats as well as loading factor. For the train's GHGs emissions calculation, we use data from Caltrain's sustainability report to calculate the per passenger per mile GHGs emissions (references in the supplementary information). Afternoon spikes are incurred during periods of online shopping for cosmetics and arranging a food delivery. Total behavioral-level GHGs was 48.86 kgCO2e.

Summed together as per equation in section 2.2, total GHGs associated with the use supply chain of this individual's ICT device use was 48.9 kgCO2e, 0.02% from the device, 0.05% from the infrastructure, and 99.93% from the behaviors.

3.2. Sources of uncertainty

Our exploration illustrates an unprecedented granular analysis of an individual's digital GHGs footprint using sampled Screenomics data in a single case study. In our analysis framework and calculation sections, we documented major assumptions with complimentary information in the supplementary section. In this section, we further discuss sources of uncertainty in this study.

(1) Manual categorization: In our initial analysis, human coders categorized device behaviors based on visits to websites or applications, and their sustainability subject expertise. For example, the checkout screen of a food or cosmetics purchase would be categorized as a purchasing activity. This activity could be further validated using transaction or survey data.
(2) GHGs emissions and activities data: As described in the method section, the GHGs calculation is based on a functionality-based LCA approach that relies on GHGs emission of specific activities and economics data with inherent uncertainties. Since the primary focus of our study is to propose a method, framework, and workflow, we do not go in-depth into scenario or sensitivity analysis to further quantify the uncertainty.

While a single case study relies on limited information from one individual, the proposed methodology and framework open possibilities to leverage new screenome data and data collection infrastructures for sustainability research. In the next section, we further discuss the implication of this method as well as future innovation opportunities.

4. Conclusion and discussion

In this study, we present the concept of DUSC as an additional dimension to view digital devices' life cycle. We propose a method to quantitatively view DUSC by applying environmental impact assessments to detailed digital behaviors. To explain how to implement such methodology, we offer a single case study to explain relevant data collection, analysis, and verification. Our case study suggests the GHGs emissions linking to digital activities is three orders of magnitude higher compared to the GHGs emissions associated with the digital devices' life cycle alone. While the initial study is conducted with single sample due to analysis resource constraint, it offers a promising possibility to the scientific community to further explore the linkage between digital behaviors and their climate impact. To conclude, we offer some additional opportunities offered by this concept in research and innovation.

4.1. Uncovering DUSC for sustainability research and practices

We present a method to apply environmental impact assessments to detailed digital behaviors, with the goal of better understanding the sustainability impacts of digital technologies. In recent sustainability research, public awareness and individual actions are considered as important levers to mitigate the impact of climate change. Some of the top GHGs emissions reduction levers include transportation mode shifts, such as living car free or avoiding transatlantic flights, or energy consumption shifts such as buying green energy, or dietary shifts to plant-based foods (Wynes and Nicholas 2017). A baseline has not yet been established regarding the extent to which digital behaviors account for individual's GHGs emissions. Screenomics paradigm enables a completely new way to observe individual-level ICT use, regardless of applications, platforms, or commercial products—details that can be linked to individual sustainability impacts. We believe our framework can leverage Screenomics and granular digital trace records to build personalized GHGs emissions baselines. A more nuanced understanding of an individual's digital life will improve baseline understanding of an individual's climate change impact, a necessity for systemic change. Additionally, as individuals rely more digital devices due to changes in work formats related to the pandemic, this proposed framework could be used to investigate the total environmental impact of these trends and disruptions. Subsequently, this analysis could help design more effective GHGs emission mitigation strategies for individuals, governments, and behavior change programs at technology firms.

There are important considerations to enable DUSC sustainability analysis at scale. First, we need to consider the ethics of analyzing DUSC. While utilizing screenshots data provides insights on the climate impact of digital behaviors, it requires careful consideration of privacy and confidentiality. The data from the Screenomics project were collected using a rigorous privacy protocol. The Screenomics project passed a comprehensive review by the Institutional Review Board overseeing human subjects research at Stanford University in coordination with the Office of Privacy and Office of Information Security (Brinberg *et al* 2021, Reeves *et al* 2019). Screenshot raw data are only accessible by trained research staff on selected computers, and during data analysis, most screens (>99%) are analyzed by computer rather than human coders. There are also efforts to minimize participants' personal or potentially sensitive information. For this study, screenshot labeling was done by a single person and commercial transaction data was masked during analysis.

Second, a data processing infrastructure is needed to support DUSC analysis at scale. In this study, we manually labeled the volunteer's digital activities to characterize purchasing behaviors. This labor-intensive analysis required about 50 h to clean the raw data, and then label and analyze all screenshots. Going forward, automating the data labeling and analysis methods could reduce time and labor. To build a baseline to connect digital behavior with anthropogenic climate change impact, we need to proactively design the data processing schemes. The current analysis just scratches the surface of the huge potential to leverage Screenomics data. The Screenomics assays include more than 1000 features, many of which are currently unexplored for sustainability purpose. For example, logo recognition and screen pop-ups might help us understand the role of advertisements, and how brand and marketing intersect with an individual's consumption behavior. Another example is analysis of linguistic features in the screenshots to provide information about perceptions and sentiments towards climate change as a topic.

Third, we need to be aware of the system boundary of the analysis and actively consider other data points. While the screen-based data represent substantial breadth of human activity, we have currently drawn the system boundary at what the digital devices can track. There are user activities that digital devices are not able to track that may have profound sustainability implications. Our approach is designed to be used as a tool to understand individual's sustainability impact through empirical data. Non-screen behaviors, captured using methods such as surveys, ecological momentary assessments, or interviews, could be combined with screen-based behaviors to triangulate individuals' climate change impacts more precisely. Community-level indicators, such as mobility and weather data, could also be combined with the screenome data and non-screen behaviors to add further context.

4.2. Opportunities for DUSC innovation towards climate mitigation

This study leverages multidisciplinary that spans product design, mechanical/electrical engineering, communication, and psychology. We summarize the opportunities for DUSC relevant innovation towards climate mitigation in this section.

There are opportunities to understand the role of digital devices in sustainability behavior and draw the difference between 'tracking' versus 'inducing'. In our exploration, we do not have a counterfactual for the case study and do not know how the user would behave in the absence of their digital devices. We can say that these GHGs emissions were 'mediated' by the digital device, but we cannot say for certain which ones would have occurred or what substitutions would have been performed without the digital device. Whereas we once had to go to brick-and-mortar stores to buy cosmetics or food, we can now use our digital devices to order them online. Furthermore, the ease of making a purchase with the touch of a button—at any time, from anywhere with Internet access—may facilitate more impulsive decision-making, which could lead to increased resource consumption. These new affordances of digital devices thus create an additional layer of separation between consumers and the production processes that sustain them, further alienating people from the resources they consume. For instance, one may be more aware of the fuel they are consuming when they must fill up their vehicle themselves, as opposed to when they order a ride from a ride-sharing app and do not need to think about gas at all. As a result, consumers may be less aware of their resource consumption when it is mediated by digital devices. DUSCs can help consumers monitor their environmental footprints more accurately, considering their shifting consumption patterns enabled by digital devices.

Currently, we have relatively little understanding of how digital devices become associated with GHG emissions. Better understanding of DUSC could help us understand the sustainability impact of new digital technology. The proposed analysis framework could also be applied to new technologies such as augmented reality and virtual reality. Since there's little information on the sustainability implications of these technologies, utilizing high frequency screenome data might help early understanding of their sustainability impact, enabling proactive policy design towards minimizing the sustainability impact of these technologies.

Screenomics is designed to be adaptable to other screens, such as TV and car screens, which could be included in future analyses (Reeves *et al* 2019).

There are also opportunities for the private sector to 'nudge' behaviors towards more sustainable options. In addition to providing general feedback and sustainability educational information on energy saving, Screenomics-based behavior recommendations could nudge users to save energy or use lower GHGs energy options. Screenomics data could be used to create dashboards for users that show personal GHGs emissions or sustainability footprint, enabling them to understand their hotspots and change specific behaviors. Additionally, personalized GHGs data could help private and public sectors promote sustainability via gamification (Chen and Cai 2019). However, we ought to understand the two sides of this effect. On the one hand, nudging individuals alone rarely achieves a big impact. On the other hand, even a small percentage change of a large user base could make a significant difference in decarbonization. We also need to consider other socio-political-technical feedbacks that lead to interactions between individual behavior, climate policy, and other consequences. Given the multiplicity of human consumption behavior, the feedback loop needs to be considered on a case-by-case basis. Going forward, we aim to automate the data labeling and analysis methods and fine our assumptions to make more accurate GHGs calculations.

DUSC analysis provides new avenues for understanding the relationships between digital device usage and environmental sustainability. We provide an early sketch of these avenues through illustrating DUSC analysis with a single case study. We thus hope fellow researchers can consider this framework and help refine its usage to uncover the nuanced ways in which everyday digital interactions contribute to climate change.

Data availability statement

The data cannot be made publicly available upon publication because they contain sensitive personal information. The data that support the findings of this study are available upon reasonable request from the authors.

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References

Belkhir L and Elmeligi A 2018 Assessing ICT global emissions footprint: trends to 2040 & recommendations *J. Clean. Prod.* **177** 448–63
Brinberg M, Ram N, Yang X, Cho M-J, Sundar S S, Robinson T N and Reeves B 2021 The idiosyncrasies of everyday digital lives: using the human screenome project to study user behavior on smartphones *Comput. Hum. Behav.* **114** 106570
Carbon Trust 2021 Homeworking report (available at: www.vodafone-institut.de/wp-content/uploads/2021/06/CT_Homeworking-report-June-2021.pdf)
Carnegie Mellon University Green Design Institute 2008 Economic input-output life cycle assessment (EIO-LCA) (US 1997 industry benchmark model) *Computer Software* (available at: www.eiolca.net)
Chen Y and Cai D 2019 Ant forest through the haze: a case study of gamified participatory pro-environmental communication in China *J* **2** 467–79
Chiatti A, Yang X, Brinberg M, Cho M J, Gagneja A, Ram N, Reeves B and Giles C L 2017 Text extraction from smartphone screenshots to archive *in situ* media behavior *Proc. Knowledge Capture Conf.* pp 1–4
Coroamă V C, Bergmark P, Höjer M and Malmodin J 2020 A methodology for assessing the environmental effects induced by ICT services: part I: single services *Proc. 7th Int. Conf. on ICT for Sustainability* pp 36–45
Darke P and Shanks G 2002 Case study research *Research Methods for Students, Academics and Professionals* 2nd edn, ed K Williamson *et al* (Chandos Publishing) ch 6, pp 111–23
de Chalendar J A, Taggart J and Benson S M 2019 Tracking emissions in the US electricity system *Proc. Natl Acad. Sci.* **116** 25497–502
GSMA 2019 The enablement effect (available at: www.gsma.com/betterfuture/wp-content/uploads/2019/12/GSMA_Enablement_Effect.pdf)
Håkansson C and Finnveden G 2015 *Indirect Rebound and Reverse Rebound Effects in the ICT-sector and Emissions of CO_2* (Atlantis Press) pp 66–73
Hittinger E and Jaramillo P 2019 Internet of things: energy boon or bane? *Science* **364** 326–8
ITU 2022 Enabling the net zero transition: assessing how the use of information and communication technology solutions impact greenhouse gas emissions of other sectors (available at: www.itu.int/rec/T-REC-L.1480-202212-I)
Judl J, Mattila T, Seppälä J, Koskela S and Kautto P 2012 Challenges in LCA comparisons of multifunctional electronic devices *2012 Electronics Goes Green 2012+* pp 1–5
Malmodin J and Lundén D 2018 The energy and carbon footprint of the global ICT and E&M sectors 2010–2015 *Sustainability* **10** 3027
Masanet E, Shehabi A, Lei N, Smith S and Koomey J 2020 Recalibrating global data center energy-use estimates *Science* **367** 984–6
Mission Innovation 2020 The avoided emissions framework (available at: https://assets-global.website-files.com/64abf03488f32826460fe327/64ad477776d4dd94cdc8fbe0_Net_Zero_Innovation_Module_2_The_Avoided_Emissions_Framework_AEF_v2.pdf)

O'Neill S, Williams H T P, Kurz T, Wiersma B and Boykoff M 2015 Dominant frames in legacy and social media coverage of the IPCC Fifth Assessment Report *Nat. Clim. Change* **5** 380–5
Ram N, Yang X, Cho M-J, Brinberg M, Muirhead F, Reeves B and Robinson T N 2020 Screenomics: a new approach for observing and studying individuals' digital lives *J. Adolesc. Res.* **35** 16–50
Reeves B *et al* 2019 Screenomics: a framework to capture and analyze personal life experiences and the ways that technology shapes them *Hum.–Comput. Interact.* **36** 1–52
Reeves B, Robinson T and Ram N 2020 Time for the human screenome project *Nature* **577** 7790
Shi L, Mach K J, Suh S and Brandt A 2022 Functionality-based life cycle assessment framework: an information and communication technologies (ICT) product case study *J. Ind. Ecol.* **26** 782–800
Snyder L V and Shen Z-J M 2011 *Fundamentals of Supply Chain Theory* (Wiley)
Suckling J and Lee J 2015 Redefining scope: the true environmental impact of smartphones? *Int. J. Life Cycle Assess.* **20** 1181–96
Wynes S and Nicholas K A 2017 The climate mitigation gap: education and government recommendations miss the most effective individual actions *Environ. Res. Lett.* **12** 074024
Yan M, Chan C A, Gygax A F, Yan J, Campbell L, Nirmalathas A and Leckie C 2019 Modeling the total energy consumption of mobile network services and applications *Energies* **12** 184