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Design for Digital Sufficiency: Understanding User Preferences for More Sustainable Data Centers

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Digital sufficiency, an emerging concept from the sustainable computing literature, can inform interface design to better manage and potentially reduce energy consumption in data centers, which is intensifying due to AI and data growth, despite energy efficiency efforts. Since 26% of data center energy consumption stems from cloud storage and servers, this research integrates digital sufficiency with existing HCI guidelines to enable cloud providers to respond to demands for sustainable infrastructure and facilitate user reflection. We conducted an online survey to understand users' storage needs, awareness of climate impacts, and openness to sustainable storage. Our findings highlight the limited awareness among users of the carbon footprint associated with data centers and a strong demand for more sustainable storage options once they become aware. To empower users to reflect on climate impacts and align storage practices with their personal sustainability goals, we propose interface design recommendations that challenge the status quo.

CCS Concepts: • **Social and professional topics → Sustainability**; • **Human-centered computing → Empirical studies in HCI;**

Additional Key Words and Phrases: Data centers, cloud storage, sustainability, adaptive design, sufficiency

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1 Introduction

To design more sustainable data centers, it is essential to address not just the efficiency of these systems [60, 108, 109] but also the sufficiency of user needs [20, 47]. By understanding what is sufficient for users and how they value environmental sustainability in the context of cloud storage, we can design interfaces that let them better align their storage practices with their preferences and collectively challenge the limited options that currently exist. The people surveyed in this study, regular users of cloud storage services, are critical because their usage patterns directly influence the carbon footprint of data centers [34]. Empowering these users with knowledge and tools to manage their data more deliberately can impact millions globally [88], offering the **sustainable HCI (SHCI)** community an opportunity to scale their research and influence [78, 98]. By focusing on sufficiency [94], this research departs from the existing one-size-fits-all approach in cloud storage and emphasizes meeting the users' needs more effectively while delivering products that prioritize sustainability, encouraging a shift toward more sufficient digital practices.

At its core, this article advocates for a paradigm shift toward digital sufficiency, a recently introduced concept from the sustainable computing literature that provides a framework for how digital technologies can become part of the essential environmental transformation. Santarius et al. [94] define digital sufficiency as *"any strategy aimed at directly or indirectly decreasing the absolute level of resource and energy demand from the production or application of ICT"*, encompassing hardware, software, user, and economic sufficiency. In the context of cloud storage, the existing one-size-fits-all approach hinders software sufficiency, i.e., minimizing data traffic and hardware utilization during application, and user sufficiency, i.e., avoiding the unnecessary or unsustainable use of digital technologies; it also reduces users' ability to use cloud storage in a way that meets their individual needs. Provided an interest in reducing their digital carbon footprint, a sufficiency-based approach to cloud storage usage could empower users to deliberately manage their data, minimizing unnecessary storage and optimizing data utilization based on personal or organizational necessities. This stands in contrast to the initially frequent but also widely criticized use of persuasive technology in SHCI [21], shifting the agency from the researcher to the user and opening up new avenues for impact.

Data centers, integral to the expansion of digital services, present significant environmental challenges due to their substantial energy consumption and corresponding carbon emissions [34, 65, 77]. Recent analyses suggest that while individual data centers have made strides in energy efficiency through technological advancements, like improved cooling techniques and hyperscale architectures, the sector's overall energy demand continues to grow [60, 108, 109]; servers and cloud storage do thereby account for 26% of data centers' total energy consumption [34]. Unlike other components, such as computing power, cooling, and networking, which are largely opaque to end users, cloud storage is directly managed and interacted with by these users. Their cloud storage data in the form of, e.g., e-mails, pictures, and automatically backed-up files, thus represents a critical point where users interact with energy-intensive digital infrastructure that is often hidden from view; oriented toward profit and growth, cloud infrastructure does not currently cater toward a user group that prefers more sustainable options (or would do so with full awareness of data centers' environmental impacts). This influence offers avenues for HCI research, in particular studies that focus on enhancing sustainability and mitigating environmental impacts [9, 12, 35, 38]. More specifically, conventional cloud storage systems typically use uniform or standardized storage policies that may not align with the diverse needs and usage patterns of individual users [81, 86, 94]. Such a generalized approach can lead to inefficiencies, including redundant data replication and excessive data retention, escalating the carbon footprint associated with cloud services.

To better understand how users interact with cloud storage services and their perspectives on the environmental impacts of these technologies, we designed a survey and conducted it on the

Prolific platform (125 responses). Chosen as a method to reach a significantly large number of users, the survey captured data on users' awareness of the carbon footprint associated with cloud storage, their current usage patterns, the factors influencing their choice of cloud provider, and their interest in adopting more sustainable practices or switching providers based on environmental considerations. It was also designed to gather information on the types of cloud services users prefer, their data volume, the frequency of their cloud interactions, and their overall satisfaction with the service in relation to its environmental impact. Based on the survey results, we propose interface design recommendations that empower users by enhancing their understanding of the energy and carbon impacts of cloud storage and providing a platform to advocate for more sustainable storage options. With the aim for users to eventually use cloud storage in a way that aligns with their personal and environmental preferences, our recommendations build on the sufficiency paradigm in combination with user-centered, reflective design principles as a way to integrate sustainable practices within the digital domain [70, 94].

We want to emphasize that our recommendations are not intended as behavior change interventions; we do not consider end users to hold power and responsibility to halt the dramatic increase in emissions associated with the operation of data centers. Especially with the recent uptake of generative AI, appropriate legislation will be required to change this trajectory. Instead, by acknowledging the insufficiency of energy efficiency and hardware/software optimization efforts in reducing data center energy consumption [21, 28], this work primarily builds a case for integrating sufficiency-based measures in interface design [69, 95]. We validate our hypothesis by demonstrating that a significant fraction of cloud users support sufficiency-based changes in cloud storage (see Section 4.4.2). As a proactive response to consumer demand, cloud providers now have a clear opportunity to reduce energy use and emissions by adopting these measures. By doing so, they can meet consumer demand and lead the industry towards a more responsible future [56, 112]. Specially, the contributions of this work are as follows:

- We provide empirical insights into user awareness, behaviors, and preferences regarding the environmental impact of cloud storage (see Sections 4.1–4.3).
- We extend these insights into practical interface design recommendations through reflective and critical design approaches (see Sections 5.1–5.4). These recommendations leverage existing SHCI guidelines to empower users (see Section 5.5).
- We contribute to a better understanding of users' preferences for reducing the carbon footprint drawing from various interpretations of digital sufficiency. This emphasizes a need for tailored cloud interfaces that enhance user satisfaction (see Sections 4.4–4.5).
- These recommendations present a unique opportunity for the SHCI community to provide tools that can be used by a large user base to gain awareness of the energy and emission impacts of the industry more widely and voice their needs [38, 62, 74]. These user preferences can collectively influence decisions around responsible innovation in digital infrastructure [56, 112].

2 Background

Data centers consume substantial energy, accounting for around 2% of global electricity usage [2]. A breakdown of this consumption reveals that servers and storage alone account for 26% of the total energy used in these facilities [34]. This consumption is further divided into energy for data processing and storage [8, 48, 77], with data centers requiring constant static power for maintaining data integrity and dynamic power for active processing [34]. Regardless of the data center's state—whether active or idle—components like cooling, networking, and other infrastructure continuously draw power. Managing data storage effectively can thus have a significant impact on static power usage and could ultimately lead to substantial reductions in energy consumption.

2.1 User-Centric Measures in Sustainable Data Management

From an HCI perspective, the efforts to reduce energy consumption in data centers, especially by cloud storage, cannot ignore the role of end users [35, 67, 73]. Much of the data stored in these facilities is personal, with users' needs directly influencing storage demand and energy use. More specifically, well-designed interfaces and systems can inform users, and enable them to express their storage needs and adopt more sustainable practices, such as data minimization and efficient data management; a process that requires active user engagements to prevent rebound effects. These effects can reduce energy efficiency savings and even lead to an overall energy consumption increase [20, 47].

For data centers, rebound effects occur as follows: As hardware and software become more energy-efficient, the costs of processing, storing, and transmitting data decrease [40, 45, 105]. This cost reduction leads to broader and more intensive use of digital services and storage solutions [60, 63]. For example, as cloud storage becomes cheaper and more energy-efficient, users and businesses are encouraged to store more data [52]. This phenomenon is compounded by a substantial growth in data generation, driven by increased internet usage, richer content formats like video and interactive media, and the proliferation of IoT devices—all demanding significant storage and processing capabilities. Thus, while energy efficiency per unit of data has improved due to innovations in server technology, cooling systems, and software optimizations, the total energy demand continues to grow because of the increasing volume of data [40, 101].

This dynamic highlights a critical challenge in sustainable technology development: efficiency gains alone are unlikely to reduce net energy consumption unless accompanied by broader, user-centric measures to manage and possibly curtail the growth in demand for these increasingly efficient technologies. Bedwell et al. [7] further emphasize the necessity of a user-centric paradigm to effectively implement energy-saving measures. Building on this work, our research captures how user-centric interface design within HCI can contribute to a transformative shift in how users engage with and impact digital systems globally.

2.2 Rethinking Cloud Services Through the Lens of Digital Sufficiency

Cloud service providers like Amazon, Microsoft, and Google have undertaken significant efforts to improve the sustainability of their data centers [81, 86]: Amazon Web Services aims for 100% renewable energy usage and has built several large-scale wind and solar farms, Microsoft Azure promotes sustainability through internal carbon taxes and renewable energy projects [81, 86], and Google Cloud claims to offset all operations with renewable energy since 2017. Keeping aside the limitations of carbon offsetting and reliability of aforementioned commitments by the cloud providers [3, 24], none of the major cloud providers have integrated tools that allow users to manage or directly influence the carbon footprint of the services they use [87, 89]. For instance, while some providers offer carbon footprint calculators or similar analytics, these tools do not empower users to actively participate in or make decisions that could lead to more sustainable usage patterns. We examine this problem through a critical HCI lens: the current sustainability efforts by cloud providers largely operate behind the scenes [71, 84], which means that users of cloud services have minimal interaction with or visibility into the sustainability practices of these providers. This lack of engagement represents a missed opportunity for HCI to increase transparency and user involvement in sustainability practices.

The relentless expansion of cloud infrastructure illustrates a traditional approach focused on technological scalability without adequately considering the finite nature of resources. For instance, Amazon Photos provides unlimited photo storage for Amazon Prime members, underscoring a marketing strategy that promotes continuous data upload without limits [57, 58]. This approach exemplifies the traditional expansion of cloud infrastructure where the provision of seemingly

infinite storage capabilities does not necessarily consider the environmental costs associated with maintaining and expanding such services. Elevating overall energy consumption and environmental footprints [87, 89], traditional approaches often fail to incorporate the necessary limits on resource utilization that are crucial for sustainable operation [97]. The presence of rebound effects further highlights the need for a digital sufficiency paradigm that not only improves efficiency but also actively involves users in reducing consumption [70, 94]. User interfaces and system designs must go beyond merely driving engagement and throughput; they should also empower users with knowledge and control over their environmental impact [88, 104].

Digital sufficiency, aiming to keep digital resource demand within sustainable limits, is increasingly relevant as we address the environmental impacts of ICT [13, 29, 94, 95]. This approach promotes efficient resource use and reduces excessive consumption, aligning with broader environmental sustainability goals. We integrate key dimensions of digital sufficiency in our work, including software sufficiency and user sufficiency [94]. This can empower users to manage their data effectively, significantly impacting the sustainability of digital systems [11, 87].

2.3 Tailoring Interface Design for Digital Sufficiency

For HCI researchers to design user-centric interfaces, it is essential to first understand user consumption preferences and then tailor these interfaces to foster user engagement and sustainable practice [9]. Tailored communication and personalized content have been found to resonate more with the specific characteristics, motivations, needs, and interests of each user [54] than generalized content [93]. In particular, users tend to benefit from being offered specific recommendations and actionable steps [41], which allows them to reduce their environmental impact in alignment with their own priorities, resources, and constraints. Deepening the understanding of cloud storage usage practices within specific user contexts could thereby provide insights into the unique challenges, motivations, and barriers users face. DiSalvo et al. [37] highlight that sustainable design in technology should prioritize user needs instead of perceiving users as problems. Building on this, research in digital sufficiency suggests balancing user needs with environmental impacts to lessen resource and energy consumption by ICT [70, 94]. For instance, Widdicks et al. [110] have explored what kind of internet use is necessary and unnecessary in their daily lives and discussed the adaptations they developed to disconnect or reduce their use. However, little research exists that involves the end user in creating adaptive functions in cloud storage from a digital sufficiency lens.

Our work prioritizes software and user sufficiency by designing recommendations for cloud storage interfaces that can be tailored to reduce environmental impacts while meeting user needs effectively [94]. In particular, we address software sufficiency by proposing interface design recommendations that enable more sufficient data management. These recommendations are tailored to reduce unnecessary data replication and excessive data retention, which are common in standardized storage policies. Similarly, for user sufficiency, we developed guidelines to engage and empower users to make informed decisions about their data storage practices. Our interface design recommendations allow users to actively manage their data—such as choosing what to store, understanding the environmental costs of their storage choices, and minimizing unnecessary service utilization. This empowerment can help users align their digital behavior with their personal environmental goals, making them active participants in reducing the carbon footprint of their data usage [11, 87, 94]. By integrating these sufficiency principles into the design of cloud storage systems, we contribute to making digital infrastructures more sustainable.

2.4 Reflective Design for User and Software Sufficiencies

Reflective design in HCI can be effectively aligned with the concept of digital sufficiency to promote user and software sufficiencies in ICTs [5]. Reflective design is an approach within design research

that aims to engage users in thought-provoking ways [96]. Rather than focusing on solving problems directly, these approaches create artifacts or experiences that prompt users to reflect on societal, ethical, or environmental challenges, which aligns with the user sufficiency dimension of digital sufficiency [94, 96].

Reflective design encompasses four resources: **temporal perspective, conversation, comparison, and discovery**, each playing a vital role in fostering sustainable user behaviors and software practices [10]. The temporal perspective encourages users to reflect on their past data usage and future needs, promoting mindful data consumption and storage practices aligned with user sufficiency, while empowering them to question and reimagine existing structures for digital engagement [39]. This resource supports software sufficiency by encouraging developers to design cloud storage interfaces that emphasize data lifecycle management, reducing unnecessary data accumulation and storage duration. Conversation fosters dialogue around the environmental impacts of data storage, involving users in the sustainability conversation. This enhances user sufficiency by making users active participants in managing their data more sustainably. For software sufficiency, it pushes for interfaces that facilitate transparent communication about the carbon footprint of storage practices and the benefits of data minimization.

The comparison allows users to gauge their behaviors against sustainable benchmarks or other users, providing a reflection point that encourages them to adjust their data usage to more sustainable levels. This resource is crucial for software sufficiency, encouraging features that allow users to see the energy consumption of storing data versus actively using it, promoting less energy-intensive practices. Lastly, discovery invites users to explore alternative ways to engage with digital content that might require less storage or lower energy use, such as streaming versus downloading. This supports user sufficiency by broadening their understanding of the environmental impact of their choices and fosters software sufficiency by integrating these alternatives into the system design.

3 Study Design

To better understand user preferences for more sustainable data centers and cloud storage, we conducted an online survey in the winter of 2024 via the Prolific platform (N=125), a widely recognized crowdsourcing platform (for demographic details of the participants, see Supplementary Text T3). We chose a survey method to efficiently gather detailed data from diverse user groups [64]. Through our survey, we gained insights into user interactions and perceptions of environmental impacts associated with their cloud storage use. By quantifying this variation, our survey data enabled us to develop tailored interface design recommendations that allow users to reflect on the energy and carbon impacts of (their) cloud storage and voice their demand for sustainable storage options [53, 100]. **User-centered design** (**UCD**) principles further advocate for initiating the design process with direct user feedback, ensuring our interface design recommendations are both theoretically sound and practically grounded in user needs and experiences, enhancing usability and adoption rates [80, 100].

Our survey consisted of 22 main questions and up to six follow-up questions and was estimated to take between 15 and 20 minutes to complete (the list of questions can be found in the supplementary material). The participants received £2.70 (£12.45/hr) as compensation for their time. Our survey targeted individuals with prior experience of using cloud storage services, e.g., Amazon Cloud Drive, Dropbox, Google Drive, IDrive, and OneDrive, among others. We deployed the survey as a **human intelligence task** (**HIT**) after conducting a pre-screening process on Prolific to ensure that participants met the eligibility criteria of having used at least one cloud storage solution. Among the pool of registered participants on Prolific, 95,206 met the eligibility criteria, and a study sample of 125 individuals was chosen randomly.

3.1 Data Collection

The questions were segmented across the following three tasks, which were designed to collect data on individual practices, environmental impact perceptions, and responsiveness to educational interventions about the sustainability of cloud storage.

Task 1. Individual practices and requirements: This task was dedicated to understanding how participants engage with their current cloud storage solutions. The questions gathered data on the cloud storage providers they had used, the amount of storage utilized, and the primary reasons for their choice of service provider, whether for device integration, unique service features, cost, or environmental considerations. This segment was crucial for establishing a baseline of user behavior and preferences, which included evaluating their payment behavior and reasons for choosing cloud storage over local alternatives.

Task 2. Perception of data centers' carbon footprint: This task aimed to assess participants' awareness and concern regarding the environmental impact of their chosen cloud storage services. Participants were queried about their knowledge of the carbon footprint associated with these services and the sources from where they had received this information. This task was critical for understanding the level of public awareness and the effectiveness of different media in disseminating information about the environmental impacts of technology use. Additionally, we explored participants' loyalty to their providers and their openness to switching to more sustainable options, providing insights into potential barriers and incentives for adopting greener technologies.

Task 3. Intervention and assessment of sufficiency: Task 3 of our survey was centered around an educational intervention that aimed to inform participants about the environmental ramifications of data centers, leveraging current research findings and illustrative visuals (see Pages 13–15 of the survey questionnaire, provided in the supplementary materials). This intervention was designed not only to inform but also to challenge participants' perceptions and predispositions toward their digital consumption habits. Following the educational intervention, we re-evaluated participants' willingness to endorse and transition to more environmentally sustainable cloud providers. Key aspects of this assessment included:

- Openness to transparency: we gauged participants' interest in choosing cloud services that offer clear and comprehensive information about their carbon emissions.
- Acceptance of higher costs: participants were queried about their willingness to incur potentially higher costs associated with greener, more sustainable cloud services.
- Tradeoffs for environmental benefits: This assessment explored participants' readiness to accept compromises in service quality, such as increased latency or reduced features, in exchange for reduced environmental impact. This is relevant to understanding how users perceive and might be willing to accept or even favor technology that prioritizes environmental sustainability over performance [12].

Task 3 was pivotal in understanding the practical implications of sufficiency for users and evaluating their readiness to adopt less resource-intensive technology solutions in their daily lives. By assessing the willingness to embrace such tradeoffs, the study contributes to the HCI discourse on designing and promoting technology that aligns with a more sustainable and sufficient use of resources.

3.2 Data Analysis

We adopted a mixed-methods approach to analyze the data collected from the survey. Quantitative data from multiple-choice questions were descriptively analyzed to identify trends and patterns within subgroups using the Qualtrics platform. In terms of qualitative analysis, we analyzed data inductively using reflexive thematic analysis [17–19]. As our goal was to identify various ways

in which cloud users would prefer to be more sustainable, the reflexive approach to the analysis was deemed the most suitable, in contrast to other approaches that prioritize the quantification of patterns and accuracy e.g., coding reliability approaches, qualitative content analysis, and so on, aligned to (post) positivist research values [18]. We conducted the reflexive thematic analysis for two open-ended questions: (1) "Would you feel better if your cloud provider started becoming more sustainable or environment-friendly? Please also explain your choice." (for results, Section 4.3.1) and (2) "Since you have told us that your cloud storage provider has unique features, please tell us about these unique features." (for results, see Section 4.5)).

We systematically coded participant responses and extracted key themes directly from the data, offering insights into user motivation and potential barriers to adopting more sustainable behaviors. We read and coded all transcripts in detail. We then discussed the codes and initial themes they identified. The analysis followed an iterative process of theme development, revisiting the data and merging subthemes into primary themes, ensuring the comprehensive theme extraction (for details about the thematic analysis, see Supplementary Text T2). We did not calculate an inter-rater reliability agreement as this is a statistical measure of agreement between coders, which is often not suitable for the reflexive thematic analysis approach that was followed by Clarke and Braun [18]. This approach facilitated an in-depth understanding of user engagement with environmental sustainability in the context of cloud storage choices. Given the method that was used, the codes were not quantified, as the goal was to identify a broad range of preferences, rather than quantify which ones were the most/least frequent [18].

3.3 Ethical Considerations

This study was conducted in compliance with the ethical standards of the University of Toronto, aligned with the Tri-Council Policy Statement of Canada: Ethical Conduct for Research Involving Humans (TCPS 2). Ethical approval for this research was secured from the Research Ethics Board at the University, under protocol number 46120. All participants provided informed consent before taking part in the study. During the consent process, participants were fully informed about the research objectives, the procedures involved, their rights as participants, and the measures implemented to safeguard their privacy and data confidentiality.

4 Findings

In the following sections, we report the varied perspectives of participants related to cloud storage and their preferences for a more sustainable storage platform.

4.1 Baseline Cloud Usage Statistics

Most participants reported using multiple cloud providers, with Google Suite being the most popular (87%), followed by Microsoft (64%), Dropbox (40%), Apple iCloud (39%), and Amazon (4%). A smaller percentage (5%) used other providers like Mega, Proton Drive, and pCloud, as shown in Figure 1(a). The primary uses for cloud storage were for backing up photos, videos, and files (80%), remote access (63%), content sharing (38%), and work-related purposes (also 38%). Other motivations were less common (5%) (Figure 1(b)). Engagement with the cloud interface varied: 28% accessed it multiple times daily, 12% daily, 38% weekly, 16% monthly, 6% rarely, and 2% never actively accessed it, relying on automated functions (Figure 1(c)). As shown in Table 1, the distribution of cloud storage usage across different providers reveals a varied range of data volume preferences among participants: 27% have 15–50 GB, suggesting a moderate need for storage. About 22% possess 50–100 GB, likely due to increasing media content and cloud service use. 13% have 100–200 GB, and another 15% exceed 200 GB, indicating substantial storage needs. The smallest group, 22%, has under 15 GB, which might reflect light usage or alternative storage methods.

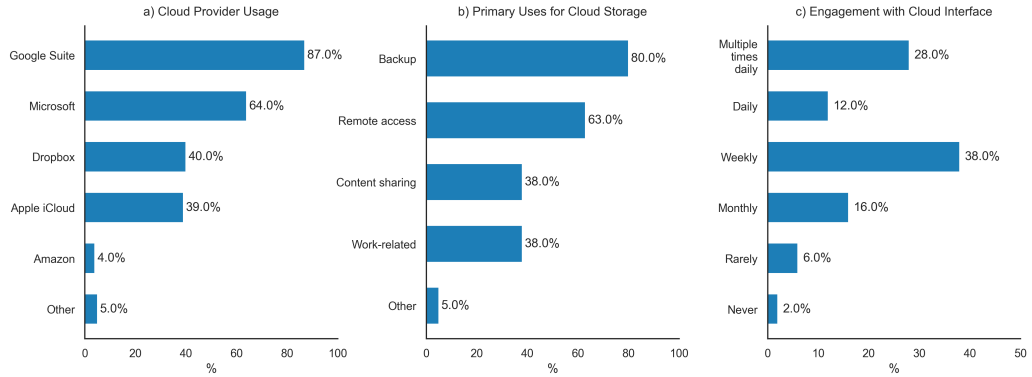

Fig. 1. Cloud Usage Statistics (a) Respondents were asked, "Which cloud storage provider(s) do you use?" to understand user preferences among available cloud services. (b) To explore the motivations behind choosing cloud over local storage, the question posed was, "Why do you use cloud storage instead of local storage?" (c) The frequency of interactions with cloud interfaces was gauged with, "How often do you access your cloud storage provider(s) on average?" This was aimed at assessing user engagement levels through activities such as storing, sharing, accessing files, checking photos, and downloading media, among others.

Table 1. Cloud Storage Distribution

Cloud Storage	Percentage	Participants	Electricity consumption by participant (in kWh)
Less than 15 GB	22%	28	18.45 (0.0-36.9)
Between 15-50 GB	27%	34	79.95 (36.9-123.0)
Between 50-100 GB	22%	28	184.5 (123.0-246.0)
Between 100-200 GB	13%	16	369.0 (246.0-492.0)
Over 200 GB	15%	19	492.0 (492.0-∞)
Weighted Average: 77.2 GB	100%	125	190

Cloud storage can be used to calculate the average electricity consumption and carbon emission: Costenaro and Duer (2012) estimated the carbon footprint for the end-to-end utilization of every GB on the internet, comprising the power consumption by the end user, transportation of data, and its storage and processing at data centers, to be 5.12 **kilowatt-hour** (**kWh**) [30]. However, we are merely interested in the role of data centers; thus, we recompute these estimates to be 2.46 kWh since 48% of the aforementioned estimates can be attributed to data centers and server rooms [1, 30]. We find that our average participant stored 77.2 GB on the cloud, placing the burden of electricity consumption at 190 kWh and corresponding CO_2 emissions of about 154.4 kilograms annually, which is based on the United States' grid's emission factor [1]. We obtain these figures by drawing from [1, 30], which uses several assumptions. These assumptions are listed in Supplementary Text T1. To put 190 kWh into perspective, consider this: the average energy consumption of an LED lightbulb is about 10 Watts. If this lightbulb runs continuously, it consumes 0.01 kWh per hour. Thus, in one year (8,760 hours), a single LED bulb consumes about 87.6 kWh. Comparatively, storing 77.2 GB on the cloud for a year consumes more than twice the energy required to power this LED bulb continuously throughout the year. According to the International Energy Agency, data centers globally consumed about 460 **terawatt-hours** (**TWh**) of electricity in 2022 [2]. To visualize this massive amount of energy, let us again use the example of LED lightbulbs. We would

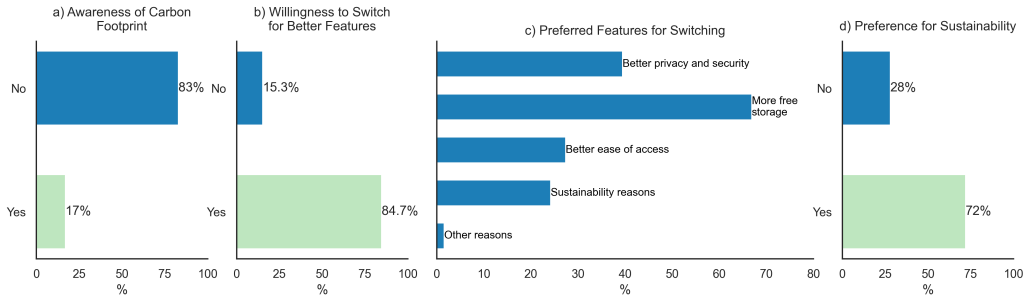

Fig. 2. Participant Awareness and Preferences Regarding Cloud Storage and Environmental Impact. (a) Proportions of survey respondents' awareness of the carbon footprint associated with their cloud storage, in response to the question: "Have you thought about the carbon footprint of your cloud storage and its impact on the environment?" (b) Distribution of respondents' willingness to switch cloud providers for better features, with the question posed as: "Would you switch if an alternative cloud provider provided better features (all other conditions remaining the same)?" (c) Preferences for features that would influence respondents' decision to switch cloud providers, following the prompt: "If yes, then select what features would help you switch?" (d) Preferences for choosing a more sustainable/environment-friendly cloud provider if respondents had to choose again, based on the question: "If you had to start over, would you choose a cloud provider that is more sustainable/environment-friendly over others?".

need around 5.25 billion LED lightbulbs running continuously for a year to consume 460 TWh of electricity.

4.2 Awareness of the Climate Impact of Cloud Storage

Participants were questioned about their awareness of the carbon footprint associated with cloud storage usage. A modest 17% of participants had considered the environmental impact of their cloud storage (Figure 2(a)). This low level of awareness suggests a potential area where HCI can play an important role. Given that the user interface serves as the primary touchpoint between digital services and users, they can be strategically designed to educate and empower users about the sustainability of their digital choices. When the subset of environmentally conscious users was probed further about how they became informed, the responses provided further insights. Social media (57%) and discussions with friends and family (48%) were the most cited sources of information, followed closely by informative videos like YouTube or TED Talks (48%). Although this was a small subset of individuals, this might indicate that casual, easily digestible, and shareable content formats are crucial in spreading awareness. Most participants reported getting news about digital technology via social media (78%) and information videos (65%). This trend underscores the growing importance of integrating interactive and multimedia content into the user interface of cloud storage services.

Although we observed a lack of awareness about the impact of cloud storage, we wanted to test the willingness of the participants to switch solely for environmental reasons. To this end, we posed a hypothetical question, wherein we provided our participants the most flexibility, "If you had to start over, would you choose a cloud provider that is more sustainable/environment-friendly over others?" and a clear majority of 72% reported affirmative (Figure 2(d)). It is worth noting that, at this point in the survey, most of these participants were not aware of the impact of data centers on the environment, yet, given an opportunity to start over, most participants exhibited a pro-environmental stance, depicting openness to an alternative option that is more sustainable.

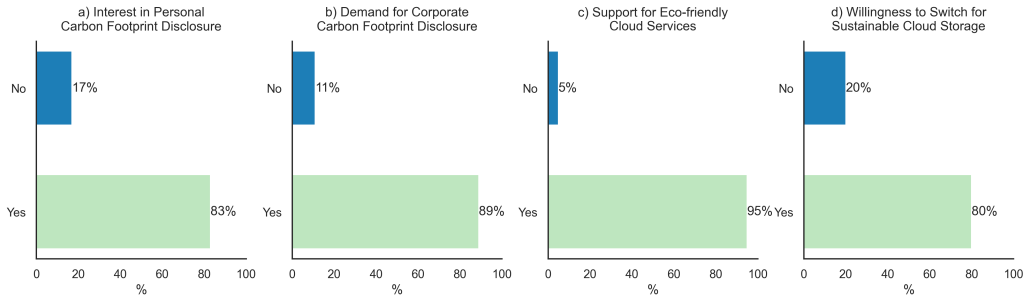

Fig. 3. Post-intervention Responses to Transparency and Sustainability Initiatives. (a) Percentage of respondents who desire their cloud provider to offer information about their individual carbon footprint, in response to the question: "Would you like your cloud provider to provide information about your individual carbon footprint?" (b) Percentage of respondents favoring their cloud provider's disclosure of their overall carbon footprint, answering the query: "Would you like your cloud provider to provide information about their overall carbon footprint?" (c) Percentage of respondents expressing a preference for their cloud provider to adopt more sustainable or environment-friendly practices, following the question: "Would you feel better if your cloud provider starts becoming more sustainable or environment-friendly?" (d) Proportion of respondents willing to switch to another cloud provider offering a net-zero plan for cloud storage, as per the question: "Suppose one of the cloud providers (Google/Microsoft/Apple, etc.) comes up with a sustainable cloud storage plan that is environmentally friendly, would you consider switching from your existing cloud provider?".

4.3 Motivations Behind Participants' Pro-Environmental Values

After presenting participants with data on the environmental impact of cloud data centers (see Task 3 in Section 3.1), we examined the extent to which they would act to support sustainable data practices in cloud storage by gauging their active and passive preferences toward it.

4.3.1 Passive Preference. We assessed the passive preference by asking, "Would you feel better if your cloud provider began adopting more sustainable or environmentally friendly practices? Please also explain your choice." Remarkably, 95% of the participants exhibited a passive preference to support sustainable data practices (Figure 3(c)). A thematic analysis revealed a significant initial reaction of surprise and concern about the environmental impact of cloud data centers (see Table 2 for resultant themes, Supplementary Text T2 for the step-by-step process, and refer to the Supplementary Materials for the coding of individual responses). For example, one participant stated, "Climate change is a real issue, and I had no idea that data centers played such a significant role in it, so I would be much happier if my cloud provider became more sustainable." This response exemplifies the significant impact of the educational intervention conducted during Task 3 of our survey on participant awareness (see Section 3.1).

We adopted a flexible approach for the thematic analysis. For instance, consider a participant's response: "I would not have to change providers [if the cloud provider adopts sustainable practices] and would still feel like I'm contributing positively." Initially, this response did not fit neatly into subthemes defined in Table 2. To address this, we merged themes by broadening their scope and interpreting the sentiments expressed more generously [17, 19]. For instance, we merged the subthemes "Personal Responsibility and Behavioral Change" and "Expectations of Corporate Responsibility" into a comprehensive theme titled "Influence on Personal and Corporate Practices." This thematic consolidation outlines the dynamic interplay between individual actions and corporate sustainability policies. Similarly, our thematic analysis identified the following refined themes:

— Collective environmental responsibility: This theme encompasses both a sense of personal duty and a call for societal and corporate accountability in environmental practices. Many

Table 2. Thematic Analysis of User Perceptions on Environmental Sustainability in Cloud Storage

Main Theme	Subtheme	Definition	Representative quotes	Comments
Collective environmental responsibility	Environmental responsibility	Expressions of responsibility towards preserving the environment and contributing to sustainability efforts.	"I believe that we all have a responsibility to preserve what we can, and sustain what we can for future generations to come."	Widespread theme across responses, showing a strong general concern for environmental issues.
	Shared responsibility	The belief that environmental sustainability efforts should be a collective societal responsibility, involving both corporations and governments.	"It shouldn't be a consumer concern, it should be the cloud provider's concern to change the way they are consuming energy."	Highlights a widespread belief in the need for systemic change beyond individual actions.
Economic realities and practical challenges of sustainability	Economic and practical considerations	Concerns about the economic impacts of sustainable practices and the practicality of implementing such technologies.	"I think it is ridiculous, which is why I would like for my cloud provider to do something about it."	Reflects consumer anxiety over the cost of sustainability and its practical deployment.
	Reluctance to change vs. necessity	Balancing between personal convenience and the imperative for sustainable practices.	"I sometimes use cloud services just out of habit even if I don't need them for this file."	Captures the tension between habitual convenience and the recognition of sustainability needs.
Educational and informational needs for sustainability	Awareness and Knowledge	Increased awareness of the environmental impact of cloud services and preference for sustainable practices.	"I didn't actually know that cloud providers and data centers have such a huge carbon footprint."	Indicates a gap in public knowledge about the environmental impacts of technology and cloud services.
	Informed decision-making	Desire for more information and transparency from providers regarding their sustainability measures.	"I would firstly like to know how environmentally friendly each provider is, and how they compare."	Indicates a strong preference for transparency to make informed choices.
Influence on personal and corporate practices	Personal Responsibility and Behavioral Change	Participants expressed a commitment to sustainable practices influenced by personal beliefs about environmental responsibility.	"Cloud computing is a vital part of my infrastructure, and knowing that it's being powered in a more sustainable way would alleviate concerns about the ecological footprint associated with my operations."	Shows personal action based on sustainability concerns.
	Expectations of corporate responsibility	Participants expect corporations to adopt sustainable practices and lead by example in environmental stewardship.	"There is a moral obligation from companies to uphold sustainable business practices."	Reflects demands for corporate leadership in sustainability.

participants expressed an urgent need for action both at individual and systemic levels. For example, one participant remarked, "Since cloud data centers contribute to 2% of global **greenhouse gas emissions** (**GHGs**), it's imperative that providers initiate sustainable practices."

— Economic realities and practical challenges of sustainability: Participants discussed the financial and logistical aspects of implementing sustainable technologies. Concerns were raised about the cost implications and the feasibility of such transformations in cloud computing. For instance, one participant said, "If my provider could offer sustainable options without a significant price increase, that would greatly influence my choice."

— Educational and informational needs for sustainability: Highlighting a lack of awareness about the environmental impact of cloud services, participants voiced a need for better information to make informed decisions. A common sentiment was, "I was shocked to learn about the carbon footprint of cloud storage; providers should be more transparent about such impacts."

— Influence on personal and corporate practices: This theme reflects the influence of sustainability on personal choices and the expectations from corporate entities (Figure 3(a,b)). Participants expressed a desire for actionable insights into how they could reduce their environmental impact and expected cloud providers to lead by example. As one participant explained, "Learning about these impacts has made me rethink my usage and expect more from my provider in terms of environmental responsibility."

4.3.2 Active Preference. While most users expressed a positive sentiment towards their providers adopting sustainable measures—suggesting a passive preference for environmental responsibility (see Section 4.3.1)—our study probed deeper into active user participation. We presented a hypothetical yet concrete scenario to the participants: the introduction of a sustainable, environmentally friendly cloud storage option by a major provider. The willingness to switch in this scenario would signify not just a preference, but an actionable intent to contribute to sustainability, even when factoring in the potential inconvenience of transitioning to a different cloud provider or the switching cost. We probed the active preferences, by asking, "Suppose one of the cloud providers (Google/Microsoft/Apple, etc.) comes up with a sustainable cloud storage plan that is environmentally friendly, would you consider switching from your existing cloud provider?"

Our findings reveal a significant active engagement, with 80% of participants indicating they might switch to a more sustainable provider (Figure 3(d)). Conversely, a minority expressed a preference to await sustainable advancements from their current provider (15%) or indicated no intention to switch (5%), citing skepticism about the individual's impact on broader environmental outcomes. One participant illustrated the dilemma between personal action and systemic change, pointing out the perceived futility of switching providers given the global scale of environmental issues and the dominant contribution of large corporations to pollution. This sentiment echoes a common frustration where individual efforts are dwarfed by industrial impacts. The findings suggest that while there is a strong preference for sustainable cloud computing solutions, there is also a clear demand for greater transparency, affordability, and responsibility from cloud providers. These insights are crucial for HCI researchers and cloud providers as they consider user motivations and barriers in the design of environmentally sustainable systems.

4.4 Preferences Toward Reducing the Carbon Footprint

Here, we examine user attitudes toward monetarily supporting sustainable cloud services (Section 4.4.1), adopting digital sufficiency-based measures (Section 4.4.2), and participating in carbon offset programs (Section 4.4.3).

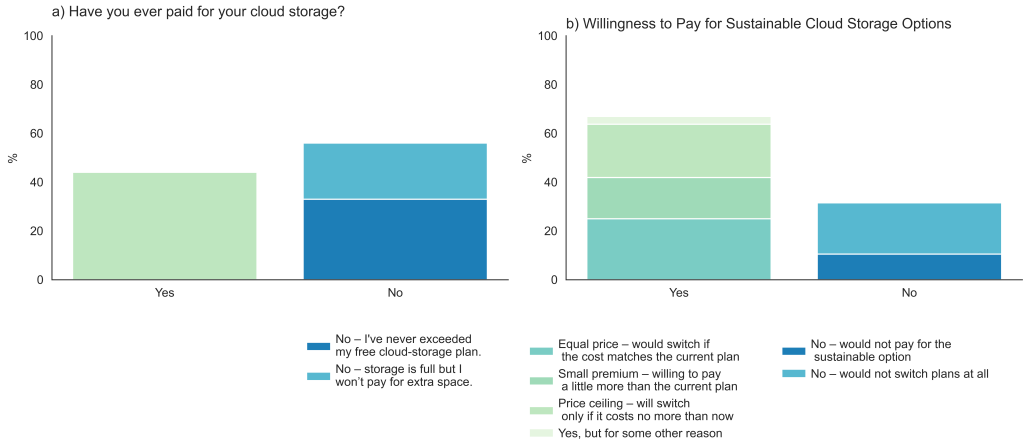

Fig. 4. Historical Payment Behavior and Willingness to Pay for Sustainable Cloud Storage Services. (a) User Payment Behavior for Cloud Storage: Responses to the survey question, "Have you ever paid for your cloud storage?" Participants indicate whether they have exceeded their free storage plan and their willingness to pay for additional storage. (b) Willingness to Pay for Sustainable Cloud Storage Options: Responses to the question, "Since you would like to switch, would you also be willing to pay for this service? Bars on the left ("Yes") are subdivided as follows: 25% would switch if the new plan cost exactly the same as their current one, 17% would accept a small premium, 22% would switch only if the price were not higher than what they already pay, and 3% cited other reasons. On the right, 11% said they would not pay for such a service, and 21% said they would not switch at all."

4.4.1 Attitude Toward Monetary Support. After observing overwhelming support for sustainable cloud storage options, we gauged if our participants would support these offerings monetarily and to what extent and compared that with their historical attitude towards cloud storage payments. In our cohort, about 45% reported previously paying to extend their cloud storage, while 22% had not paid despite reaching their storage limit, indicating a reluctance to incur additional costs (Figure 4(a)). Conversely, 33% had not exceeded their free storage limits and thus had not faced a decision regarding payment. Subsequently, we asked the subset of our participants (80%) who would consider switching to more sustainable cloud providers if they would also be willing to pay for this service. A staggering 85% reported a willingness to pay for this service: 32% of these respondents would pay the same as their current plan, while 28% were willing to pay but not more than their current plan. On top of that, approximately 21% of respondents were even willing to pay more for a service that is environmentally friendly, underscoring the importance users place on the environmental impact of their digital consumption (see Figure 4(b), which presents these statistics for the entire cohort, in contrast to the subset of participants expressing a willingness to switch as discussed in the text).

Comparing participants' historical attitudes towards cloud storage payments with those due to environmental reasons revealed the following insights:

— Among those who had paid for additional storage in the past, 79% were willing to switch and invest similarly in a sustainable cloud storage service.
— Out of those who had utilized only the free storage and had never paid, 54% indicated a willingness to switch and pay for a sustainable cloud storage service.
— The group that was most reluctant to pay initially, having not paid despite full storage, showed a notable shift: 61% were willing to switch and pay for environmental reasons.

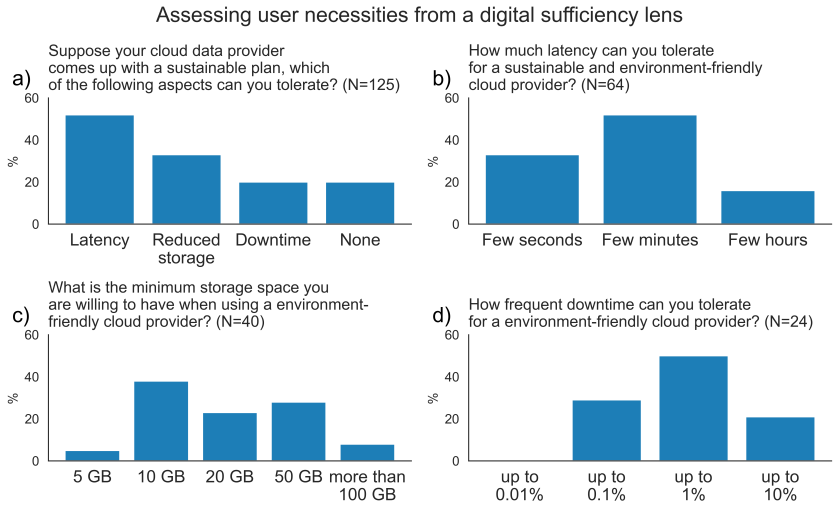

Fig. 5. Assessment of user necessities through a sufficiency lens. Participants were surveyed on their tolerance levels for sustainability tradeoffs with cloud data providers, namely (a) general willingness to accept sustainable practices, (b) tolerance for latency, (c) minimum acceptable storage space, and (d) acceptable downtime frequency. Sample sizes are indicated for each sub-figure (*N*=number of responses).

These descriptive statistics not only demonstrate a robust user interest in supporting sustainable cloud services but also indicate a significant portion of the user base is prepared to back their environmental concerns with additional financial outlay. This indicates a strong demand for sustainable cloud storage solutions, as users actively seek to reduce their carbon footprint through their choice of cloud services.

4.4.2 Attitude Toward Digital Sufficiency-Based Measures. Previous research on sustainable cloud computing typically addresses sustainability through technological and policy innovations without critically examining the necessity of growth itself (see Sections 2.1 and 2.2). In contrast, a sufficiency-oriented approach in the context of cloud storage challenges the inevitability of growth by advocating for a re-evaluation of user needs [92]. Our survey explored users' openness to reassessing their cloud storage needs to align with environmental sustainability goals. We surveyed users on their willingness to adapt to changes that would limit their full-service utilization and, consequently, the environmental impact of cloud services. The survey asked participants to consider scenarios where their cloud provider implements a sustainable, environmentally friendly strategy, potentially involving tradeoffs such as increased downtime, increased latency, or reduced storage capacity.

Figure 5 indicates that a significant majority (80%) of our participants are open to these digital sufficiency-based measures. They expressed a willingness to accept slower synchronization speeds (52%), smaller storage allocations (33%), and more frequent downtime (20%). Notably, among the participants who were willing to tolerate smaller storage space, 43% were amenable to limiting their storage to 10 GB or less. Current cloud providers typically offer a non-negotiable free plan of up to 15 GB, indicating a gap between user willingness for sufficiency and provider offerings. Participants also reported tolerance for sync delays ranging from a few seconds (33%) to several minutes (52%) and downtime of 1 day in 100 days (50%) as opposed to the standard 1 day in 10,000 days (99.99% availability). This openness to digital sufficiency suggests a shift in user perception toward prioritizing environmental considerations over maximal service utilization. However, current

cloud provider interfaces lack mechanisms that support users in making informed decisions about reducing their digital footprint. We provide design recommendations for such mechanisms that could encourage users to critically evaluate their actual data needs versus their environmental impacts, fostering a more sustainable approach to digital technology use (see Section 5).

4.4.3 Attitude Toward Carbon Offsets. We further assessed users' willingness to adopt monetary mechanisms that compensate for their carbon emissions when sufficiency measures alone are insufficient for net-zero emissions. Probing the question about carbon offsets indirectly, we asked the participants which features they believed would contribute to making a cloud platform environmentally sustainable. The majority of participants (84%) recognize the importance of utilizing renewable energy sources as the primary power supply. This approach directly reduces the carbon footprint associated with cloud services by shifting the energy reliance from fossil fuels to cleaner alternatives. A significant number of participants (57%) advocate for strategies to integrate sufficiency-based features to reduce carbon footprints, indicating an interest in active user engagement in reducing emissions. Additionally, sustainable e-waste management is considered important by 67% of the respondents, highlighting the role of responsible end-of-life practices for electronics in the overall sustainability of cloud platforms.

When it comes to carbon offsets—a financial tool to compensate for emissions—the enthusiasm appears to be more tempered: a smaller proportion of participants (25%) see the value in carbon emission offsets through flexible payments. This suggests that while there is some support for offsetting carbon emissions financially, it is not as strongly favored as the direct use of renewable energy (84%) or sufficiency-based features (57%). This suggests that while users recognize the role of economic transactions in supporting environmental goals, they seem to prefer direct, tangible actions over indirect financial strategies like carbon offsets.

4.5 Decoding Brand Loyalty and Switching Behavior

Previous studies have examined user behavior through the lenses of brand loyalty and brand switching [44, 111]. In our research, we explored these concepts among cloud storage users by first identifying their motivations for selecting their current cloud providers, and then by directly questioning their openness to switching brands. Participant responses to why they chose their current cloud storage providers were categorized into two groups: those who made intentional choices due to perceived unique features or other reasons, including sustainability, and those who made unintentional or sporadic choices, often influenced by the availability of a free plan or default installation on their device.

Our findings indicate a significant trend toward unintentional selection, with 63% of participants indicating such choices, compared with only 9% who chose intentionally, whereas the rest reported a mix of both unintentional and intentional choices. Furthermore, although 29 participants initially cited unique features as their reason for selection, a closer examination—through thematic analysis—reveals these features to be common across several platforms. This thematic analysis focused on categorizing responses based on the intrinsic characteristics of cloud storage services, such as synchronization, data sharing, and enhanced storage options. For example, as shown in Table 3, the ability to sync data across devices was mentioned as a unique reason for choosing a provider like Google, yet this feature is widely available across all major cloud providers (see Table 3 for resultant themes, Supplementary Text T2 for the step-by-step process, and refer to the Supplementary Materials for the coding of individual responses). This widespread misconception calls into question the existence of genuine brand loyalty in this market. Notably, this distinction emphasizes fundamental attributes of cloud storage services as opposed to perceived differences by the users.

Table 3. Thematic Analysis of Unique Cloud Storage Features

Theme	Definition	Count	Representative quotes	Implications
Synchronization	Ability to sync data across multiple devices.	6	"sync app data across devices", "good sync between devices"	Common feature perceived as unique, influencing unintentional brand loyalty due to ease of use and device compatibility.
Data sharing	Features allowing users to share data with others.	7	"Share with up to five other peoples", "Being able to share documents and files between users"	Considered unique by some users, but generally standard across platforms; emphasizes the role of collaborative features in user retention.
Enhanced storage options	Features related to the expansion and management of storage space.	11	"large amounts of storage available for low cost", "can keep up old data and restore deleted data"	Perceived as unique but widely available; highlights how storage flexibility and recovery options can influence user choice, often without true differentiation.
Data protection	Includes encryption and data recovery options.	3	"Encryption of data", "Repair deleted data",	Security features are critical but not unique, though they are often decisive factors in provider choice due to safety concerns.
Integration with other services	Integration with other applications and services for enhanced functionality.	6	"OneDrive syncing with my Password Manager", "It is providing us with SharePoint where we give every individual access to the company documents"	Users perceive integration capabilities as unique, impacting loyalty, even though such features are common across many services.
Ease of use	User-friendly interfaces and automatic operations.	5	"can update on itself", "easy to organize documents/files and share them"	Interface and usability may be seen as unique to individuals, influencing their choice, despite being a common trait among competitors.
Cost efficiency	Affordability of the service, including free options and low-cost upgrades.	3	"You don't pay for storage", "cheap enough to pay for"	Free options and low-cost upgrades are nearly universal across cloud providers, yet their perceived uniqueness underscores a gap.

Indeed, when participants were asked if they would switch providers if superior features were offered elsewhere, a substantial 85% expressed willingness to switch, prioritizing more free storage (67%), enhanced privacy and security (39%), and better access (28%) as their main reasons. Even among the participants who reported choosing a cloud provider for sustainability reasons, no particular cloud provider stood out as sustainable. These results underscore a highly volatile consumer base in the cloud storage market, with limited evidence of true brand loyalty and a high propensity to switch providers for better features.

A comparison of the two switch-intention questions (this one and another in Figure 5) shows they tap complementary motivations rather than conflicting ones. While 80% of respondents said they might move to a greener provider and 85% would switch for clearly superior features, most participants (≈72%) endorsed both reasons; 13% would switch only for better features, 8% only for sustainability, and just 7% for neither. This pattern suggests that strong environmental credentials are now approaching the status of a baseline requirement–on par with traditional feature improvements–rather than being viewed as a tradeoff.

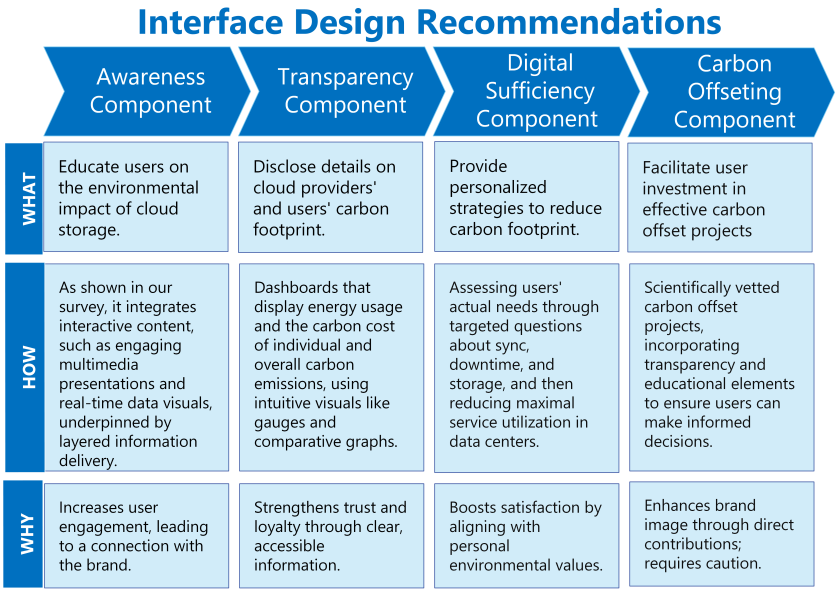

Fig. 6. Overview of the proposed interface design recommendations for the cloud providers, highlighting the aims (What is the purpose of the component?), implementation approaches (How should the components be implemented?), and anticipated outcomes (Why should HCI researchers design the component?). While the 'why' column may suggest benefits for cloud providers, the primary aim of these components is to cultivate user awareness and enable users to engage in sufficiency-based measures for sustainability, reflecting the dual goals of user empowerment and ecological responsibility.

5 Discussion

Our study reveals a critical gap in sustainability practices in the current state of cloud data centers [22, 37, 51]: despite the strong user demand for sustainable cloud storage options (see Section 4.3), major cloud providers have yet to implement user-centric strategies that effectively reduce carbon footprints. In addressing the ecological responsibilities of cloud providers, HCI researchers can play an important role in shaping the interface and interaction strategies that can drive sustainable practices. While cloud providers must adopt greener practices and communicate the environmental impact of their services transparently, HCI researchers can augment this by designing intuitive interfaces that make these disclosures actionable and understandable. Operationalizing the recently introduced concept of digital sufficiency within interface design, our work emphasizes the potential of the HCI community to directly influence the sustainability outcomes of a large user base by embedding them into everyday digital interactions.

Drawing from the insights obtained from our survey, we provide interface design recommendations for HCI researchers that can help meet user expectations for functionality while advancing sustainable practices; these recommendations include four key components, each tailored to enhance user engagement with sustainable practices (Figure 6). The **Awareness Component** aims to educate users about the environmental impact of their data usage, utilizing interactive tools to visually demonstrate these effects. The **Transparency Component** seeks to build trust and promote responsibility by providing clear, detailed information about both the user's and the provider's carbon footprints. The **Digital Sufficiency Component** offers personalized strategies for reducing carbon output, enabling users to customize their data practices. Finally, the **Carbon Offsetting**

Component facilitates direct environmental action by linking users to vetted carbon offset projects, thereby making it easier for users to contribute to environmental sustainability initiatives. Each component is informed by the positive feedback and the openness of our participants toward these components during our survey. By developing these systems, HCI researchers can transform raw data into actionable insights that users can act upon.

Our survey findings also reveal a low level of brand loyalty within the cloud storage provider market, presenting a substantial opportunity for HCI researchers to innovate through tailored services (see Section 4.5). This lack of loyalty opens avenues for the design of novel, personalized services that align closely with individual users' sustainability preferences. By tailoring interface components to meet these unique user needs, there is even potential to cultivate brand loyalty for sustainable cloud providers in the future. Users are more inclined to establish a bond with brands that reflect their personal values, thereby enhancing user engagement and satisfaction [44, 93, 111].

5.1 Awareness Component: Educating Users on the Environmental Impact of Cloud Storage

Our study demonstrates a critical gap in public awareness regarding the environmental implications of cloud storage usage. More specifically, 83% of survey respondents reported being unaware of the environmental impact associated with cloud data storage (see Section 4.2). The importance of higher user awareness cannot be overstated. As Dourish [38] highlights in his discussion on HCI and environmental sustainability, the role of user awareness extends beyond individual behavioral change to encompass broader systemic transformation. His successful case study of using mobile phones as environmental sensors exemplifies how HCI can be leveraged to increase environmental awareness. This approach not only informs individuals about their personal impact but also integrates them into larger ecological assessments, thereby fostering a more profound and collective environmental consciousness [85, 106].

Existing HCI literature on developing engaging content delivery methods can help create engaging, interactive educational content that highlights the energy consumption and carbon emissions of data centers [14, 16, 33, 66, 90, 102]. This might also mimic the successful awareness strategy that was used during Task 3 of our survey (see Section 3.1), utilizing multimedia presentations and real-time data visuals. In our survey, the educational intervention was methodically designed to educate participants on the environmental implications of cloud data storage, adopting a two-step approach that is anchored in the principle of layered information presentation [26, 75]. In the first step, we set the stage by establishing the pervasive impacts of climate change on the environment, drawing upon credible sources like OxFam and National Geographic (see Task 3 in Section 3.1). This was achieved through visuals and concise, impactful text that emphasized extreme weather events as tangible consequences of climate change, a strategy that aligns with HCI recommendations on the use of relatable imagery and succinct information to quickly engage users and convey urgency [26, 75]. The second step bridged the gap between the broader environmental issues and the specific contributions of data centers to climate change. By providing factual data, like the percentage of GHGs attributable to data centers and their comparison with other national totals [34, 60, 108, 109], we delivered a focused message on the significance of digital sustainability.

To further inspire the design of an Awareness Component for cloud provider interfaces, interactive elements [43, 68], such as simulations or calculators, could be used, allowing users to visualize the relationship between data storage and carbon emissions. Approaches for effective awareness could even include more playful methods, such as gamification [23, 36, 42, 59, 76], whereby it remains essential to not use these approaches to shift the main responsibility for reducing the carbon footprint of cloud storage to individual users.

5.2 Transparency Component: Detailed Carbon Footprint Disclosure

The findings from our survey reveal a strong desire for increased transparency regarding environmental impacts: 83% of the participants expressed a keen interest in understanding their personal carbon footprint related to their use of cloud services. Moreover, an even higher percentage, 89%, indicated a desire to be informed about the overall carbon footprint of their cloud providers. To provide users with transparent information about the cloud provider's carbon footprint and the user's personal contribution to it, we call for an integration of a Transparency Component within the cloud provider's interface. We recommend implementing clear, easy-to-understand dashboards that display both overall and individual carbon footprints, inspired by the survey's feedback on user preferences for straightforward, actionable data. This component's design should enable the tracking of energy usage at data nodes in data centers, translating this consumption into carbon emissions based on emission factors relative to the energy source's renewability. These data should be visualized in an intuitive and accessible manner, fostering transparency.

The interface could, for instance, use gauges, graphs, or comparative metrics, enhancing user engagement and promoting environmental stewardship. Drawing from [30], the Transparency Component could adopt the approach outlined for calculating the electricity consumption of data in cloud storage. Their analysis suggests that the internet uses an average of about 5 kWh to support the utilization of every GB of data. This information could be incorporated into the component, providing users with feedback on the energy impact of their stored data, reflecting the direct carbon cost implications for the environment. Previous research has highlighted that while end users bear only 38% of the carbon costs of internet activities [30], there is a societal cost with the remaining carbon cost spread over the global internet infrastructure. By embedding this understanding into the Transparency Component, cloud providers can educate users on the wider impact of data usage, potentially influencing more eco-conscious data management and fostering demand for more sustainable cloud services. For instance, HCI designers could develop interfaces that provide feedback on the carbon footprint associated with users' data storage. Such feedback mechanisms could serve to educate users about the less apparent environmental costs of their digital activities and empower them to make sustainable choices.

5.3 Digital Sufficiency Component: Personalized Reduction Strategies

This component aims to empower users to define and apply personal sufficiency measures to reduce their carbon footprint, enhancing user autonomy in cloud storage practices. A surprising 80% of our participants were open to integrating sufficiency-based measures to optimize their data storage and reduce unnecessary carbon emissions (see Section 4.4.2). We recommend that this could be done by a component that adopts a two-pronged approach: first, it gauges users' willingness to adapt to environmentally friendly practices via a series of targeted questions that assess their actual needs regarding various aspects of cloud service usage. These questions, which can be borrowed directly from our survey (see Figure 5), aim at discerning users' thresholds for aspects such as data synchronization latency, storage capacity, and acceptable levels of service downtime. Subsequently, this component uses user-generated data to tailor the cloud infrastructure to individual preferences, thus aligning service provisions with user values. For instance, if user responses indicate a lower necessity for rapid synchronization, the service can be adjusted to have longer intervals between syncs, thereby reducing server load and energy consumption. Such a personalized approach does not merely conserve resources; it also deepens user engagement by aligning service operations with personal sustainability goals [70, 110].

We also advocate for the inclusion of educational components within the cloud provider interface so that users can understand the tradeoff between their convenience (e.g., immediate data synchronization, minimal downtime, and considerable storage) and reduced environmental impact,

and how it can lead to reducing the energy-intensive operations of cloud services. The interface can offer personalized recommendations and step-by-step guidance on data organization strategies [41], empowering users to actively participate in eco-friendly data practices. HCI researchers can design interfaces that resonate with the personal environmental values of the users by integrating digital sufficiency measures within these systems. This reduction in maximal service utilization creates a dual benefit: a stronger connection between users and the fate of their data and a tangible reduction in emissions [85]. The design of such systems within HCI must be carefully considered to ensure they remain user-centric, transparent, and directly aligned with the overarching goal of sustainable digital practices.

5.4 Carbon Offsetting Component: Facilitating Indirect Action

The Carbon Offsetting Component aims to provide a user-friendly interface that facilitates direct investment in carbon offset projects. By recommending projects that are verifiably effective and align with the user's sustainability values, the interface intends to harness user participation in carbon mitigation efforts more effectively. Yet, the efficacy of such carbon offsetting methods has come under scrutiny. Previous research reveals that the scientific legitimacy of carbon offsetting is contentious, with arguments presented that such strategies may, paradoxically, contribute to a net increase in global emissions [3, 24]. These critiques emphasize that offsets, rather than preventing emissions, may inadvertently support high-carbon infrastructure and detract from more effective mitigation actions like direct renewable energy investments or efficiency improvements. These findings also resonate with the sentiments captured during our survey, where enthusiasm for carbon offsets was notably muted (see Section 4.4.3). Only 25% of participants saw the value in carbon emission offsets through flexible payments, indicating a preference for more direct interventions over financial transactions that indirectly contribute to environmental goals. This contrasted starkly with the 84% of participants who supported direct use of renewable energy and the 57% who favored sufficiency-based features.

From an HCI perspective, this raises critical design and ethical considerations. How can we ensure that the interface design of the Carbon Offsetting Component transparently reflects the nuanced efficacy of carbon offsetting and does not perpetuate the inadvertent support of infra-marginal, non-additional projects? Previous research suggests a cautious approach, where the value proposition of such a component must be critically assessed against the empirical evidence to avoid reinforcing ineffective environmental strategies [3, 24]. Incorporating such a component warrants a thoughtful interface design that emphasizes transparency and user education, enabling users to make informed decisions about their participation in carbon offsetting schemes. We find ourselves at a crossroads, acknowledging a subset of participants who support carbon offsetting while also considering the growing body of research suggesting its potential inefficacy [3, 24]. Our stance on integrating this component remains inconclusive, reflecting the complexity of translating such nuanced environmental policies into actionable HCI design strategies. Cloud service providers looking to appeal to environmentally conscious consumers should prioritize integrating direct sustainability features into their services. This includes leveraging renewable energy, enhancing transparency and control over carbon footprints, and facilitating responsible e-waste management.

5.5 Situating our Design Recommendations Within Existing SHCI Guidelines

The proposed interface design recommendations align with the **user empowerment framework** outlined in Prost et al. [88]. The Awareness Component fosters a deep environmental consciousness by educating users on their digital activities' environmental impact, resonating with the framework's emphasis on "Awareness of Responsibility." The Transparency Component provides users with actionable data about their carbon footprints, bridging the gap between awareness and

understanding, and equipping users to make informed decisions about their environmental impact, thus aligning with "Taking Action" and "Shifting Perspectives." The Digital Sufficiency Component empowers users to implement personal sustainability measures, encouraging collective action and aligning with "Overcoming Inability to Act" and "Reaching Out to Stakeholders." These components collectively support a comprehensive approach to sustainability, mirroring the framework's call for a holistic approach to environmental impact and collective action.

Our interface design recommendations extend the **user engagement principles** outlined in Clear et al. [27] to the domain of cloud services and data management. While Clear et al. [27] emphasize the role of pervasive sensor data and interactive energy-use interventions to enhance user engagement and promote sustainable thermal comfort in workplaces, we apply these principles to the digital realm by advocating for user-centric measures and feedback mechanisms for digital sufficiency. By encouraging users to minimize their digital footprint through informed decision-making, our interface design recommendations underscore the role of feedback in raising awareness and promoting energy conservation.

The proposed interface design recommendations are also grounded in **existing SHCI strategies** for raising awareness in the context of environmental sustainability. For instance, the Awareness and Transparency Components aim at enhancing user awareness of pro-environmental behaviors and deepen understanding of emissions impacts through information dissemination. HCI researchers have successfully done this previously using digital tools (e.g., apps, interactive platforms, **virtual reality** (**VR**), and **augmented reality** (**AR**)) [49, 50, 72, 91], television/internet platforms (e.g., documentaries, online forums, and social media) [31, 32, 107], workplace digitalization (e.g., dashboards for real-time tracking and comparison) [68, 82, 83], and virtual or real-world incentives [25, 42, 103]. For instance, previous research has successfully utilized Google Earth and other digital mapping tools to enhance students' understanding of ecological issues and global environmental changes through spatial visualization [49, 91].

The **Digital Sufficiency Component** is predicated on HCI strategies that have been effective in fostering user engagement and promoting environmental responsibility. Research demonstrates that digital tools have been successfully used to educate people on environmental issues, leveraging real-time feedback and social benchmarking to enhance awareness and drive sustainable practices. Ostertag (2023) highlights that such tools not only raise awareness but help normalize sustainable behaviors through transparency and collective action [82, 83]. Furthermore, interactive technologies, including virtual simulations, play a significant role in environmental education. These technologies, capable of simulating complex ecological processes, enhance users' understanding and engagement with sustainability issues. For example, virtual environments have been utilized to educate users about biodiversity and conservation, offering immersive experiences that deepen understanding and encourage engagement [23, 36, 42, 43, 59, 76]. This approach aligns with the **Hybrid Model** suggested by Markowitz et al., which integrates digital tools with traditional educational methods to strengthen learning outcomes and promote the practical application of environmental knowledge [72]. This integrated approach underpins the Digital Sufficiency Component, designed to engage users comprehensively in managing their digital consumption to achieve sustainable outcomes.

While this hybrid approach offers an innovative strategy for environmental education, addressing the issue of emissions from data centers requires more than education alone. The proposed Digital Sufficiency Component tackles this by engaging users in understanding what sufficiency means for them, enabling them to take control of their emissions. This initiative opens up discussions on how to "calibrate" user experiences to achieve a "good enough" level that satisfies user needs while prioritizing resource savings. Echoing **Sustainable Interaction Design (SID)** principles proposed by Blevis, the Digital Sufficiency Component focuses on efficient resource use and product longevity, foundational elements for minimizing environmental impact through deliberate design choices

[15]. SID also advocates for designs that enable renewal and reuse, thereby extending the useful life of products. This philosophy aligns with the Digital Sufficiency Component, which involves users in the process of understanding and managing their digital consumption effectively, leading to reduced emissions from data centers and other infrastructural components. For example, the emphasis on reusing existing systems rather than disposing and purchasing new ones underpins the concept of sufficiency by optimizing and extending the lifespan of current resources.

Despite the strengths of these proposed components, a significant gap remains: these components have not yet been implemented. To truly empower cloud users, HCI researchers must design these components [88]. By incorporating these components, they can transform the user experience from one of passive consumption to active participation in sustainability efforts. This would align with the principles of collaboration and social responsibility, ensuring that users are not left in a state of helplessness but are instead equipped with the tools and knowledge to make meaningful changes.

5.6 Resolving Power Imbalances and Emphasizing Hardware and Economic Sufficiencies in Cloud Computing

After introducing the four components, a valid question arises: How do hardware/software optimization efforts or energy efficiency measures balance with sufficiency-based measures in data centers? Additionally, what role do sufficiency-based measures play alongside these energy-efficiency and optimization measures? Enhancements in hardware and software efficiency can lead to rebound effects where the increased efficiency invites greater usage, thus neutralizing potential reduction in energy consumption and environmental benefits (see Section 2.1). This phenomenon is well-documented in studies by Coroamă & Mattern (2019) and Gillingham et al. (2016), which highlight how efficiency gains can paradoxically lead to higher overall consumption [28, 45]. Consequently, while technological optimizations are essential, they are not sufficient by themselves to guarantee sustainable outcomes, particularly when the rapid growth of data necessitated by advanced computing technologies, including AI, is significantly increasing the energy consumption of data centers [6, 99]. Thus, sufficiency-based measures, which actively manage and occasionally restrict usage to align with individual sustainability goals, are crucial not merely to balance but to counteract the rebound effects of energy efficiency-based efforts [94].

Still, while integrating sufficiency into interface design is pivotal, it forms only a part of the solution. Critically, the core issue revealed by our survey is the lack of awareness among users about the carbon footprint associated with cloud storage (Figure 2). This unawareness is not the fault of the users but is a problem of information accessibility and corporate transparency. When informed, a significant majority of users showed enthusiasm for digital sufficiency measures, without the need for further nudges or behavior change technologies (see Section 4.4.2). This underlines the necessity of reflective interface design in engendering awareness. However, to provide a holistic approach to digital sufficiency in cloud computing, it is crucial to also address the often-overlooked aspects of **hardware and economic sufficiencies**. A comprehensive approach necessitates the implementation of robust hardware sufficiency strategies. For instance, Santarius et al. discuss strategies like designing devices to last longer, using fewer resources, and maintaining minimal absolute energy demands for operations [94]. Additionally, economic sufficiency strategies are vital for reshaping economic incentives to foster sustainable industry practices. Santarius et al. suggest promoting business models that prioritize public and common goods and reducing economic growth as the primary goal, thus supporting a transition to an economy that operates within ecological limits. Such measures directly contribute to lowering the carbon footprint but must be supported by industry-wide changes and stringent regulations to ensure a substantial impact.

Yet, the economic structures underpinning current technological advancements favor continuous growth and consumption, often at the expense of environmental sustainability. Economic

sufficiency implies reshaping these economic incentives and structures to support sustainable practices across the board, not merely at the user level. It involves advocating for policies like carbon pricing and stringent regulatory caps on energy use, which can align the profit motives of big tech companies with the sustainability goals of the broader community. Our recommendations stem from a foundation in reflective design, which aims not to alter user behavior but to fundamentally shift the relationship between technology and society. This, coupled with economic and hardware sufficiencies, can catalyze significant changes in how data centers operate, making them accountable to the global community they serve. By framing technology within reflective design [96], we can empower users to become active participants in understanding and addressing climate issues. Further, through the critical design of the technology [39], we can critique the lack of transparency and accountability in the operations of data centers. The technology can also be designed to illustrate the collective influence users could wield by demanding sustainable practices from the providers.

Addressing the economic incentives for providers and users is crucial. As noted, reducing the carbon footprint can decrease operational costs for providers while not necessarily lowering costs for users. This disparity highlights the need for mechanisms that ensure benefits are shared equitably, such as offering incentives for users who opt for greener services. While our interface design recommendations are designed to enhance user sufficiency and promote sustainable practices, they should be seen as part of a broader, multi-dimensional approach. Effective transformation toward sustainable cloud computing requires integrated strategies that encompass user behavior, system design, and, critically, the economic and regulatory frameworks that shape these technologies' deployment. Only through such a comprehensive approach can we hope to achieve the substantive reductions in resource and energy use that are necessary for environmental sustainability in the digital age.

6 Limitations

Online surveys are a convenient, inexpensive, and widely used data-gathering tool; however, they can come with two inherent limitations [4, 79]: the individual characteristics of the population that takes the survey cannot be fully described beyond their demographic details, and respondents with biases may deliberately opt to be part of the sample. To counter these limitations, a random selection of registered participants on Prolific was invited to our survey, which facilitated the recruitment of a diverse and statistically significant sample of 125 participants. Prolific's participant selection algorithm ensured a standard distribution across various demographic factors, including birth countries, spoken languages, resident countries, sexes, ethnicities, student status, and employment status (see Supplementary Text T3). The sample exhibited a balanced gender representation, with 54.4% of the participants identifying as female. Despite these strengths, the generalizability of our findings may be limited by the overrepresentation of white ethnicity and younger individuals, as 62% of participants identified as white, in addition, most of our participants were below 40 years old. Such demographic skew may influence the applicability of our results to more ethnically and age-diverse populations. As a result, future research may benefit from adopting prospective quantitative data gathering approaches other than surveys to investigate preferences toward sustainable cloud storage.

Social desirability bias in surveys is the tendency of respondents to answer questions in a manner that will be viewed favorably by others, often leading to the overreporting of positive behavior and underreporting of negative behavior [79]. Although it cannot be completely avoided, we have used the following methods to minimize the extent of it: (1) indirect questioning, i.e., to assess sensitive attitudes toward environmental responsibility without directly querying participants on their personal commitment to carbon reduction, we ask them to rank and compare multiple

options; (2) neutral wording, i.e., efforts were made to employ neutral wording in the descriptions and questions related to climate change and the impact of data centers; and (3) anonymity, i.e., to encourage more honest responses, particularly in questions related to personal habits and choices regarding technology usage and environmental impact, the survey was designed to collect data anonymously, assuring participants that their responses could not be traced back to them. We also randomized the sequence of response options where applicable. This technique helped to prevent order effects, where the position of items could influence responses, and minimized the likelihood of response biases that could occur if participants consistently chose the first or last option they were presented with.

7 Conclusion

Before turning to concrete implications, we invite readers to pause and reflect on a simple but often-ignored insight from our survey: many users accept sufficiency (e.g., lower-sync speeds, smaller storage quotas, or scheduled downtime) not because they are "giving something up," but because those extras were never genuinely useful to them in the first place. What looks like restraint is, for a significant share of participants, merely an alignment between real needs and real use. This finding shows the deeper problem of over-provisioning of features by cloud providers (and Big Tech more broadly): by treating maximal performance and limitless capacity as universal defaults, providers pre-empt the kind of everyday reflection that lets people decide what suffices for their own work and values. Designing interfaces that foreground sufficiency, therefore, does more than curb energy demand—it restores agency by normalizing the individual reflection on "How much is enough for me?"

The goal of this research is to motivate HCI researchers and cloud providers to implement sufficiency-based measures in their interface design. This can become possible through engendering awareness, ensuring transparency, and assessing an individual's tradeoff for sufficiency. Simultaneously, this research advocates for more stringent regulations and the obligatory disclosure of carbon emissions among cloud providers, a measure supported in other sectors [61]. Hussain et al. [55] critique the sustainability reporting practices in data centers, highlighting prevalent "greenwashing" tactics—where data centers underreport their actual carbon footprint through the acquisition of green energy credits or certificates. This means that careful attention needs to be paid when cloud providers implement the aforementioned design recommendations, to ensure that their reports are accurate and that individual users are not held responsible for unsustainable choices made by companies. This article presents a shift towards sufficiency in digital systems, advocating for a framework that is not only efficient but also firmly rooted in ecological imperatives and active user engagement. By harnessing HCI principles focused on empowering users and fostering ecological awareness, cloud services can be transformed into platforms that encourage sustainable consumption behaviors and significantly reduce the environmental footprint of digital infrastructures.

8 Future Work

Having established that (i) users are willing to adopt sufficiency-based measures and (ii) four high-level interface components can enable that adoption, the work now moves from "what" to do to "how" to build it: the next research priority is the collaborative creation and evaluation of concrete wireframes and full user-interface prototypes that embody those components. With the aim of promoting user autonomy and sustainability in cloud-storage platforms, we propose that these follow-up efforts focus on designing interfaces that are both transparent and capable of personalising sufficiency-based measures. Through participatory design, users can actively shape these interfaces, ensuring they cater to diverse needs and preferences, while flexible customisation

will let individuals tune storage features to their own definition of "enough." In line with well-established HCI design guidelines [46], prototypes should undergo iterative refinement driven by comprehensive user feedback so that the final versions are both functional and user-friendly. By delivering interfaces that resonate with users and encourage thoughtful interaction, future work can foster a culture of sustainability within the cloud-storage community. Cross-disciplinary collaboration will be integral to this process. Expertise from HCI, climate science, life-cycle analysis, and computing is needed to ensure that the resulting interfaces meet technical requirements and align with user needs and sustainability goals. Because the survey asked the two switching questions separately (for better features and or sustainability), participants did not directly rank or choose between sustainability and superior features; future work should present the options side-by-side or use conjoint analysis to obtain a finer-grained prioritisation. Ultimately, the overarching objective is to empower users with the tools and information required to make informed decisions about their data usage while actively contributing to environmental sustainability in the cloud-storage ecosystem.

Supplementary Information Statement

The data supporting the findings of this study are available within the supplementary materials of this publication. The supplementary materials include the anonymized survey questionnaire, the collected responses from participants, coded themes for the results in Tables 2 and 3, and the Supplementary Text T1, T2, and T3. Supplementary Text T1 comprises assumptions for Table 1, Supplementary Text T2 details the process of thematic analysis conducted for Tables 2 and 3, and the Supplementary Text T3 comprises demographic information about our participants.

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