Harvesting Light, Cultivating Care: Exploring Intermittence As Framework for Infrastructuring and Stewardship

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In response to growing environmental concerns within the Human-Computer Interaction (HCI) and Design communities, recent efforts in both industry and academia have focused on addressing the sustainability and environmental impact of technological interventions. This paper engages with this discourse by investigating the lived experiences of volunteers stewarding solar powered servers within the Solar Protocol experimental network, a distributed collaborative design provocation that merges creative practice, sustainable computing, ecological awareness, and community-based care. Through interview analysis, triangulated with additional data sources (observations, memos, communications, etc.), we examine how stewards of cyber-physical systems interdependent with built and natural environments across varied geographies confront and adapt to infrastructural intermittency. We foreground the sociotechnical dimensions involved in this reinfrastructuring process, as the system's design influences collective maintenance efforts. Our findings highlight how stewarding systems that are intermittently powered fosters stewards' deeper understanding of infrastructural interdependencies and environmental rhythms, positioning intermittence as a generative framework for sustainable infrastructural awareness and adaptation.

CCS Concepts: • **Networks** → **Network manageability**; • **Human-centered computing** → **Collaborative and social computing theory, concepts and paradigms**.

Additional Key Words and Phrases: Care, infrastructuring, intermittence, maintenance and repair, limits, sociotechnical systems, stewardship, sustainable HCI

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1 Introduction

Concerns regarding the environmental sustainability of Human-Computer Interaction (HCI) and Design practices have spurred significant research efforts over the past fifteen years and across multiple communities. The perspective that environmental considerations should guide our actions has become a cross-disciplinary ethos, with HCI scholars undertaking systems-level investigations of climate change with a wide range of stakeholders [40], addressing the materiality of digital infrastructure [45], embracing more-than-human approaches to broaden perspectives on climate challenges [51], and responding to calls for climate justice through inclusive, community-driven practices [66]. In this evolving landscape, new approaches that center ecological thinking in order to foster more environmentally conscious ways of being have flourished in a variety of research and practice-based communities. Particularly the Workshop on Computing within Limits community, or “LIMITS” for short, situates current computing research within an ecosystem of constraints, ranging from the limits of extractive practices to the biosphere’s capacity to recover from human impact, as well as the boundaries of knowledge and technological capabilities [54]. This interdisciplinary research community has been actively challenging the predominantly growth-oriented visions of innovation and technological interventions for a decade [58], while interrogating the role technologies can effectively play in addressing climate-justice related limits through new computing imaginaries [54].

Solar Protocol, an experimental network of solar-powered servers distributed across the globe, responds to this call to action through a public social invitation to explore principles of “Energy-Centered Design” [10] to reframe planetary boundaries [70] and energy intermittence as creative opportunities rather than constraints, and to help realign us with natural phenomena. Research estimates that by 2025, the IT industry could use 20% of all electricity produced and emit up to 5.5% of the world’s carbon emissions [35]. A growing proportion of IT energy consumption comes from data centers used to store data and computer hardware, almost always plugged directly into the local electricity grid [67]. Yet, we tend to think of the Internet and its infrastructure as something immaterial, and refer to it by using misleading language such as “Cloud” and “Web” which contribute to its further detachment from the natural world and the concrete resources it consumes to power the flow of billions of online posts and transactions. What began with the provocation *“How would your relationship with the Internet change if it were powered by the Sun?”* developed, over the course of two years, into a distributed community of solar-powered servers stewarded by self-motivated individuals (and small groups) interested in exploring natural rhythms as logic, rather than extractive ways of being. The project enabled us to explore the relationship between intermittence and stewardship of infrastructure in the context of these servers. In the face of the current and future climate crisis, amplified by the exceeding of planetary boundaries [79], learning more about infrastructure and actively participating in its stewardship emerge as imperative strategies for mitigating current and future environmental impact.

Infrastructures can be defined as the foundational systems and structures that support the functioning of societies and economies, which provide the necessary backbone for everyday operations and services [9, 23]. Our current infrastructures play a critical role in resource consumption, energy usage, and global emissions and necessitate a collective commitment to responsible design and management. Infrastructures, often viewed as engines of ontological change [38], sit at the intersection of people, technology, and the environment and play a pivotal role in shaping our understanding of the world. Although accountability and responsibility mostly lie, at scale, in the practices of large corporations and institutions, it is undeniable that we as individuals, but also as collectives, hold power through our informed decisions and actions. To this effect, in the pursuit of more just, socially, and environmentally sustainable futures, CSCW, an intrinsically ecological discipline [42], offers both analytical lenses and generative models. More recently, the CSCW and (E)CSCW communities have delved deeply into the practicalities of infrastructuring as collaborative design [83], acknowledging and discussing what is genuinely being implemented in shaping our sociotechnical landscapes while paying close attention towards the embedded complexities, ambiguities, tensions, power dynamics, and politics inherent in these collaborative settings [12, 38, 52, 56].

In this paper, we present an analysis of findings from an inquiry into the experience of six volunteer stewards across six sites of the Solar Protocol network. Across two years, the stewards each built, maintained, cared for and engaged with a locally hosted solar-powered server, connected to a global network of computers through the wider network of Internet infrastructure. We conducted surveys and interviews to understand how the stewards hosted and cared for this distributed technical system, and to learn what can motivate, support, or hinder collective infrastructural stewardship. We triangulated the survey and interview data with data from the stewards' implementations of the Solar Protocol including researchers' communications with stewards, one-on-one technical onboarding and troubleshooting sessions (both at their sites as well as remote), online communications among stewards on Solar Protocol's Discord server, as well as the researchers' own observations and reflections from their personal experiences as server stewards and broader stewards of the project. Our thematic analysis wants to shed light on the following research questions:

- **RQ1** - How do stewards mentally and physically situate their solar-powered infrastructure?
- **RQ2** - How does the intermittent nature of the project influence stewards' environmental and infrastructural awareness?
- **RQ3** - What, if any, practices of care emerge from their participation in this distributed experiment?
- **RQ4** - Can participating in stewardship of intermittent systems foster imaginative and creative problem solving?

Our study contributes to understanding how stewarding cyber-physical systems, interwoven with natural and built environments, can foster a richer comprehension of infrastructure's materiality and fragility, particularly in relation to ecological forces. These insights demonstrate that stewardship, while varied and challenging, provides valuable avenues for developing care and maintenance practices aligned with sustainability goals. The study suggests that engaging with infrastructural limitations can inspire sustainability-oriented design and artistic experimentation, prompting a rethinking of resilience within environmental constraints. By embedding sustainability within infrastructural practices, our findings aim to inform a broader discourse on computing consciousness and sustainable design, positioning intermittence not merely as a condition but as a generative framework and motivating force, beyond awareness.

2 Solar Protocol

Solar Protocol is a Web platform hosted across a network of solar-powered servers deployed around the planet (Fig. 1). A solar-powered server is a small low-power computer (RaspberryPi) hosting digital content, powered by a 50W photovoltaic (PV) panel and a small rechargeable battery. Each server only offers intermittent connectivity that is entirely dependent on available sunshine, battery capacity, length of day and local weather patterns at each site. When connected together to form a network, the servers are designed and programmed to coordinate to serve the website from whichever location is enjoying the most sunshine at the time. With servers located in different time zones, seasons and across different weather systems, the network directs Internet traffic to whichever is generating the most energy. The Solar Protocol network explores the Sun's interaction with Earth as a form of natural logic that shapes the daily behaviors, seasonal activities and decision

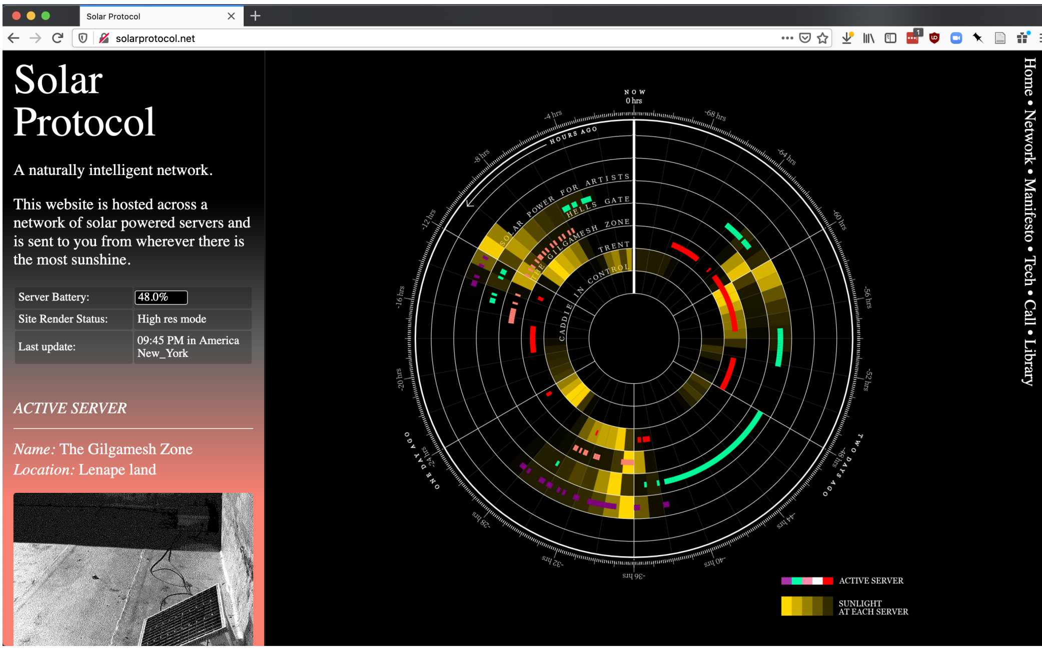

Fig. 1. Solar Protocol Web Platform hosted at solarprotocol.net

making of almost all life forms. Solar Protocol wants to honor this logic, embracing it as a form of natural intelligence to be used to automate decisions in a digital network. Over the course of a year and half, Solar Protocol grew from a small scale experiment (with three test nodes in one city stewarded by three of the authors) to an internationally distributed prototype with twelve servers (Fig. 2) located in eight countries across six continents, five different time-zones and a wide range of climates (The Netherlands, Kenya, China, Australia, Canada, Dominica, Chile and the United States). All nodes are stewarded by volunteers such as community organizers, technologists, multimedia artists, entrepreneurs, educators, researchers and scholars.

3 Background

3.1 Sustainable HCI and Computing Within Limits

Within Human-Computer Interaction, sustainability has been a matter of deep concern for the last couple of decades [25, 40]. A sustainability-forward agenda within HCI (SHCI) has grown out of the 2007 paper where Blevis argued for principles of repurposing and reuse, towards Sustainable Interaction Design (SID) [6], against the more popular cycle of invention and disposal. Considering that computing underpins nearly all aspects of today's global infrastructure, from agriculture, communication, finance, transportation, science, education, healthcare, governance to artistic and creative practices, the way we envision and materialize computing holds tremendous potential to address or impact global limits [69]. Re-envisioning computing can contribute to redirecting our society towards more meaningful acknowledgement and response to these constraints.

An active cross-disciplinary community of scholars spanning computer science, engineering, information science, ecology, environmental sciences, and science and technologies studies (STS), has formed around the "design and development of computing systems in the abundant present for use in a future of limits or scarcity" [57], appropriately called Computing Within Limits, or

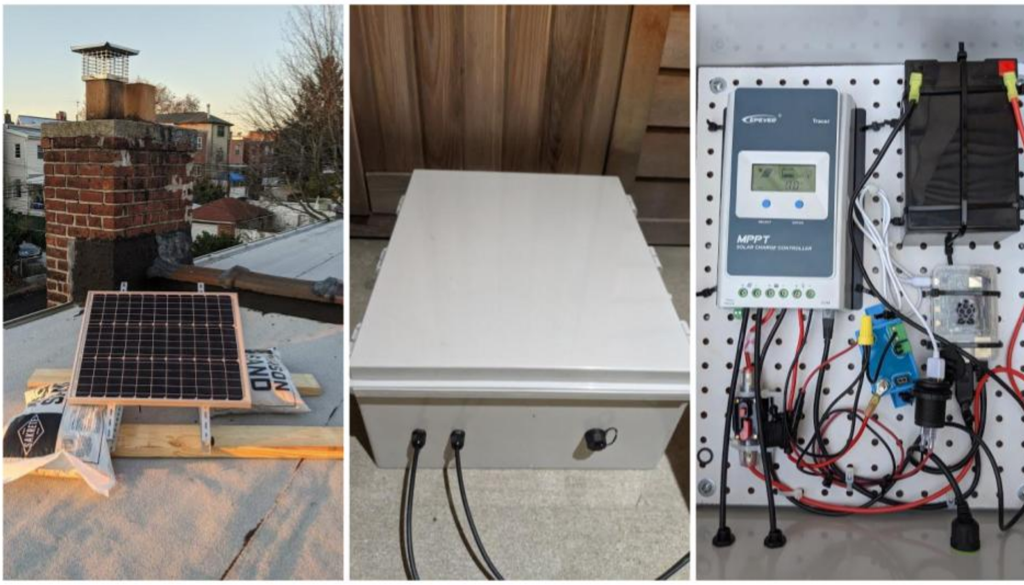

Fig. 2. A solar-powered server installed on the roof of a building and its components

LIMITS for short. We would argue that this constrained future is actually at our doorsteps, as Rockström and colleagues have been demonstrating [70], and LIMITS researchers have responded by investigating degrowth in computing [36] by re-imagining the development of physical and digital technologies through principles of constraint and restraint such as adopting practices of re-use, repair, and non-waste [1, 16, 54, 68, 80]. Informed by scenarios of degrowth in the global economy [13, 50], permacomputing, for example, experiments with the application of permaculture principles to the digital domain [16, 17, 84], while low-carbon methods of academic research focus on preparing academic practices for intermittence and inevitable energy transitions [59, 60, 62]. In this study, we extend the LIMITS community's exploration of sustainability by positioning the Sun as an intentionally limited, intermittent energy source, demonstrating how intermittence can serve as a productive design framework for developing resilient, resource-conserving systems. This work expands on Liu's contributions, which emphasize designing around intermittency not as a flaw but as a feature [44]. By centering Solar Protocol's design around the intermittency of solar power, we offer new perspectives on how constraints and temporal rhythms can inspire creative approaches to computing, reshaping how we envision the future of infrastructure in a world increasingly defined by its limits.

3.2 Infrastructuring and Re-Infrastructuring

"*Infrastructuring*", a key concept in the Computer Supported Cooperative Work (CSCW) community, views infrastructure as a dynamic and evolving process rather than a static end product [56, 65, 77]. This perspective emphasizes that infrastructure must be continuously developed and reconfigured in response to changing needs, technologies, and contexts [37]. Infrastructuring is about embracing a process ontology and recognizing that the act of building infrastructure not only solidifies existing relationships but also reshapes them [8]. Unlike traditional notions of infrastructure as fixed, infrastructuring involves users, stakeholders and community members actively participating in shaping and maintaining these systems [47]. This ongoing engagement and adaptation are referred to as "*re-infrastructuring*" [29], highlighting the need for infrastructures to remain flexible and responsive over time.

"*Infrastructural inversion*", as described by Bowker and Star [76], involves surfacing the often invisible layers of infrastructure to reveal the social, political and technical systems that underpin them. Normally, infrastructure operates in the background until it fails, but infrastructural inversion encourages critical reflection on the power dynamics and institutional arrangements that govern infrastructures, revealing the strategic gatekeeping and regulatory frameworks that often remain hidden [9]. By making these concealed elements visible, users and researchers can gain a deeper understanding of the power dynamics and institutional constraints embedded in infrastructures, leading to more informed and participatory approaches to their design and upkeep.

3.3 Infrastructure Stewardship Framed Through Care, Maintenance and Repair

Stewardship, whether in environmental, digital, or infrastructural contexts, inherently interweaves with maintenance and care practices. Stewarding infrastructure involves a moral and practical responsibility for its sustained health, resonating with maintenance and care ethics [33, 81]. This study positions stewardship as a multi-dimensional role, grounded in the ethical considerations of sustaining systems for long-term resilience, where maintenance becomes a central aspect of this ethical commitment.

3.3.1 Care. Care ethics, rooted in feminist theory [26, 27], offers a relational framing for stewardship, emphasizing continuous engagement with both technical and ecological needs [85]. By embracing care as an ongoing commitment [22], this approach highlights the interconnectedness of infrastructures with societal and ecological systems, advocating for a model that extends beyond individual interests to prioritize collective well-being [81]. This framing is particularly relevant to our study, where stewards' daily practices of server maintenance highlight a responsive form of care, encompassing attention to the underlying infrastructures of their communities. In digital contexts, stewardship involves not only maintaining technology but safeguarding its cultural and historical significance, as seen in Digital Stewardship Programs that encourage community-led design and local capacity building [18].

Stewards must balance technical responsibilities with the ecological and social contexts they operate within, often requiring them to navigate unfamiliar or unpredictable environmental and infrastructural dynamics. The voluntary nature of stewardship can further complicate long-term sustainability, as maintaining motivation and capacity over time, especially with limited resources, can be difficult [2]. Our study highlights the importance of community-oriented knowledge exchange and echoes calls for the broader ICTD and CSCW communities to prioritize local capacity-building and meaningful engagement in design, moving beyond technical solutionism [20, 71] toward sustainable practices grounded in care [82]. Centering care, maintenance, and repair could be productive for the LIMITS research community, as it challenges traditional technology design by foregrounding the essential, continuous work required to maintain, repair and overall steward, our *"fractal world, a centrifugal world, an always-almost-falling-apart world."* [33].

3.3.2 Maintenance and Repair. In this study, we position the stewards' work within the broader context of maintenance and repair, seeing their actions as inherently tied to acts of care [34]. *"Infrastructures fail everywhere, all the time"* as Shannon Mattern recounts, and there is invaluable knowledge to be gained by studying how things get put back together [48]. Studying the practices of maintenance offers insights into the hidden labor necessary to sustain technology, especially intermittent, ecologically tethered systems [28, 33, 48]. Maintenance and repair practices involve technical expertise and a commitment to troubleshooting within fluctuating environmental contexts, tasks often undervalued yet essential for sustainable stewardship [73]. By embedding maintenance and repair within stewardship, this research underscores their role in enhancing infrastructural resilience through continuous engagement with both social and environmental infrastructures.

4 Methods

4.1 Timeline of Activities and Authors' Positionality

The work reported on in this study spans three years of data (2019-2022). In 2019, the authors were part of a research project focused on developing a single solar-powered website [64], which became the technical foundation for expanding into a solar-powered network of servers [4]. The decision to frame the project as a collective experiment emerged from the authors' desire to move beyond localized or individual-scale experiments common in low-power computing, permacomputing and similar fields [1, 46, 61, 80]. Our aim was to introduce a wider variety of social, cultural and geographical contexts to expand the scope of lessons learned and share these insights back with interested communities. This approach organically inspired a more globally distributed experiment, increasing the diversity of perspectives and practices that would inform the development and maintenance of the network.

In the second phase of the project, in 2020, three prototype nodes were established within a single urban geographical area to assess the technical feasibility of creating a distributed network of solar-powered servers. Upon completing this phase, the authors issued a public call for stewards in the same year, inviting global volunteers to participate in the project by building and maintaining their own server nodes. Server stewards were recruited to join the Solar Protocol experiment through a number of channels: an online call for participation, word of mouth among creative research communities and direct recruitment or inquiry. In total, more than sixty individuals (and small collectives) submitted an expression of interest form, from Europe (16), Africa (19), Asia (4), United States (20), South America (1), North America (1) and Australia (1). We originally employed a purposeful sampling approach [24] to select stewards targeting geographical distribution, and ultimately stewards' criteria for participation focused on volunteers' interest in sustainability and their willingness to engage with the technical and community aspects of the project. Funding was available to cover the cost of the hardware for each server and the stewards' time commitment to this study. In this expanded capacity, the authors also took on the roles of server stewards, engaging directly in the building, installation and maintenance of the software and hardware architecture necessary for the network. Additionally, they were responsible for the coordination, communication and community management aspects of the Solar Protocol project. Throughout the project's evolution, stewards were kept informed of opportunities and developments through individual communications, email newsletters, remote conferencing and announcements on the shared Discord server. In 2022, after the stewards had been engaged with the project for about one-to-two years, we recruited a subset to do reflective interviews and surveys.

4.2 Participant Recruitment

The server stewards are volunteers and represent the complex human side of Solar Protocol's cyber-physical infrastructure tasked with its maintenance and care. At the point of highest participation, the Solar Protocol network was hosted across twelve servers, spread across six continents (Asia, Africa, North America, South America, Europe and Australia), over five time zones and maintained by approximately twenty individuals. Stewards' diversity spanned across geography, age, background, expertise, ethnicity, identity, occupation and affiliations. Stewards' engagement with the project tends to be intermittent. This fluctuation is often influenced by external factors, such as other professional responsibilities, project opportunities, troubleshooting needs or participation in public-facing events. Stewards are generally more available when they require support or when their immediate involvement in the project is necessary. In 2022, the research team shared an invitation with the stewards to contribute their experiences to this research study. Six server stewards opted to participate based on their availability and ongoing engagement with the Solar Protocol platform. To acknowledge their time and contributions during the interviews, stewards were offered a small stipend.

4.3 Participant Steward Profiles

The findings of this paper center on six Solar Protocol server stewards that represent contexts across six countries and four continents. The stewards are self-driven tinkerers and makers, organizers, educators, creatives, technologists and designers who are deeply invested in their local contexts and approach technologies from the perspective of the potential benefits they can bring to their communities [74]. The diverse personal and professional identities of stewards are directly linked to their unique stewardship experiences as their participation is often driven by personal values and professional goals. This diversity in backgrounds and motivations means that each steward brings a unique perspective to the project (and to this study), influencing the way they engage with their servers and their approach to maintenance, repair and care.

4.3.1 Canada Server Steward. ***AP*** is an interdisciplinary researcher and faculty member whose work spans climate communication, environmental humanities, and Science and Technology Studies (STS). Their research focuses on how carbon is communicated across diverse communities and media, exploring the political and material impacts of these interactions. AP's server was installed at their home in Canada, on a patio, after their institution declined to host it due to networking and installation concerns. During the COVID-19 lockdown, AP shifted their research activities to their home, sourcing materials locally and assembling the server with remote assistance through a two-hour video call. AP's initial plan was to use the server to host their research group's website on low-carbon academic practices, with broader aspirations for a public data visualization art project, and future plans to engage with the local community.

4.3.2 United States Server Steward. ***CS*** was at the time an engineering and environmental studies student with a focus on energy humanities, who originally collaborated with another student on their application to become a solar server hosting site. The other student graduated by the time this study began. The server was installed at their University on the East Coast of the United States (Fig. 3), on the balcony of their research lab specializing in sustainability engineering. The stewards acquired, fabricated and installed the server on campus entirely on their own with almost no support from the team. CS had received a University grant to support the purchase of the hardware and the steward was hoping to use the solar server and the Solar Protocol open API as part of their thesis capstone experience to explore solar data sonification.

4.3.3 Caribbean Server Steward. ***SJ*** is a technologist known to the team thanks to their ongoing work on a community WiFi network they jump started after the devastation left behind by Hurricane Maria on the island of Dominica, in the Kalinago Territory (Fig. 3). They also work for the local government and oversee resilient technology projects in anticipation of future climate change events. The server was shipped to the steward partially assembled as the cost of components was prohibitive for local sourcing, and it was assembled by the steward at the local Community Resource Center. SJ had experience doing computer repair and joined as a solar server steward with hopes to digitally archive local Indigenous practices and media content created by youth in the community, on an independently hosted server that anyone could access, especially during emergencies.

4.3.4 Kenya Server Steward. ***DW*** originally applied to become a solar server steward as part of a local collective of young engineers/hobbyists working in technologies across energy, agriculture,

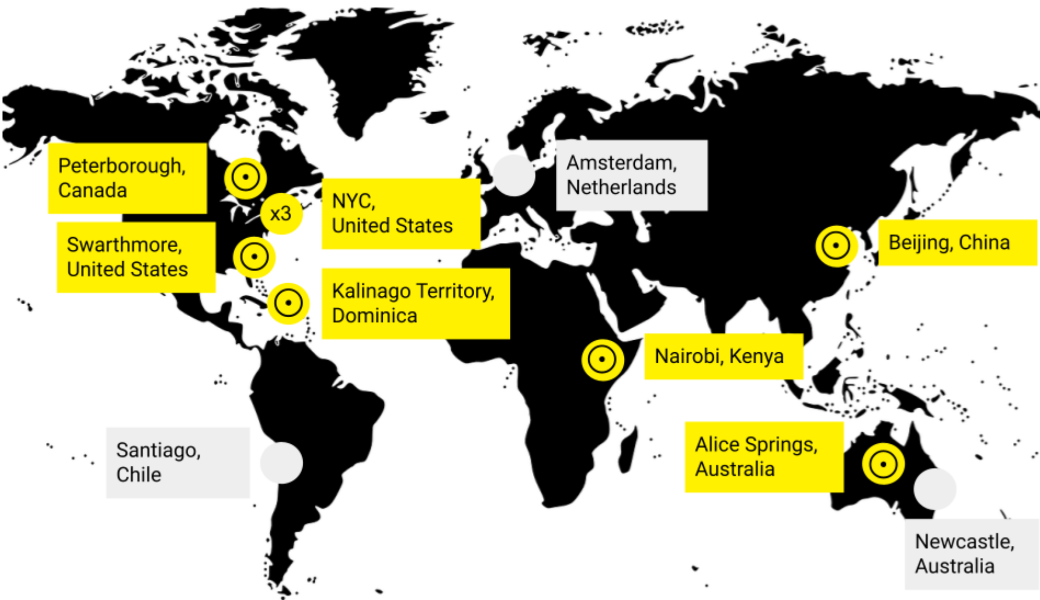

Fig. 3. Map of all server locations at the time and of those stewards who participated in this study

water and the environment in Kenya (Fig. 3). DW is a software engineer working on decision-making systems in finance and robotics with a deep passion for gaming. They came to the Solar Protocol project guided by their personal curiosity around what a minimal and decentralized Internet might look like. DW sourced the most cumbersome elements locally and assembled the server which had been shipped as a kit with step-by-step instructions. The server was then installed on the balcony of their apartment building with the goal of experimenting with solar-powered lo-fi decentralized gaming and worldbuilding applications.

4.3.5 China Server Steward. ***BC*** is a digital creator and faculty member in Experimental Art in China, working at the intersection of technology and art. Their involvement with Solar Protocol began when they initially inquired about featuring the project in an art exhibition, which required a physical server on site and eventually led to their stewardship. BC sourced all materials locally and built the server independently, except for some software support to navigate local Internet restrictions. The server was first installed on the rooftop of the gallery hosting the exhibition and later relocated to their office balcony at their institution. By keeping the solar server on campus, BC hoped to encourage students to reflect on the environmental impacts of computing.

4.3.6 Australia Server Steward. ***CB*** is a community technologist and journalist located in the Northern Territory of Australia. Their practice focuses on using technology to amplify marginalized histories, stories and languages through collaborative art and media projects. At one point, CB contributed to the deployment and stewardship of two solar-powered servers in separate Territories (Fig. 3). By the end of the study, their server was installed at a local artist-run initiative: a former petrol station turned into gallery and community space in one of Australia's sunniest regions. Sourcing most materials locally, CB built the server with a local collaborator with some support from a team member. CB saw the server as a fitting tool in the community to facilitate conversations around extraction, collective resource use and relationships to the natural environment, informed by the local Indigenous culture engaged in sustainable land stewardship.

Steward Name	Location	Host Site	Institutional Support	Community Ties	Goals for the Server
1. **AP**	Canada	🏠	✔	✔	Research, Art & educational resource
2. **CS**	USA	🏫	✔	✔	Research, Art & educational resource
3. **SJ**	Dominica, W.I.	🏫	✖	✔	Off-grid community media archiving
4. **DW**	Kenya	🏠	✖	✔	Software development & games
5. **BC**	China	🏫	✔	✔	Research, Art & educational resource
6. **CB**	Australia	🏫	✖	✔	Research , Art & media archiving

Fig. 4. A snapshot of the six profiles of the server stewards who participated in the study

Although the range of applications for the Solar Protocol infrastructure ranged dramatically from web hosting, public art making, to digital archiving and beyond, all of the stewards shared a driving motivation and sensibility towards sustainability in computing and media (Fig. 4) and deep community ties. Despite the many differences in backgrounds, contexts and geography, the research also uncovered common threads and themes across the stewards' experiences.

4.4 Interview and Survey

The aim of the interviews and surveys was to gain insights into the communities, histories, and practices in which the stewards' servers were situated, as our understanding of their unique contexts was initially limited. We conducted semi-structured interviews with each steward remotely that lasted approximately 60-150 minutes. One interview took place through a back-and-forth email correspondence. The mode of the interview (video conferencing, audio conferencing or email correspondence) as well as the duration of the interview varied based on time zones and each site's level of access to a reliable broadband connection. The interviews were structured into three parts: the first part focused on their motivations for joining the project (RQ1), their experiences so far with stewarding a piece of intermittent infrastructure (RQ2, RQ3), and their goals for the servers (RQ4); the second part focused on what specific skills, tools, resources would be helpful in supporting stewards' and their communities' goals, while the third part focused on tools and platforms we could leverage to build community among the Solar Protocol stewards (RQ3).

The stewards also completed a 16-question survey which focused on capturing background knowledge, comfort levels with various technologies involved in Solar Protocol (e.g., photovoltaic systems, hardware, software, networking) and their personal interests and motivations. The survey was meant to complement the interview by gathering insights into how stewards' passions inform their engagement with the infrastructure (RQ1), and to help the researchers plan for future activities.

As part of this research study, server stewards were involved in the member checking process to ensure that their perspectives were accurately and appropriately represented [49]. After the initial analysis of interviews, the manuscript was shared with the stewards to review, provide feedback and correct any potential misrepresentations and ensure their experiences and insights were truthfully captured. In this process, all stewards opted to have their real names used, choosing not to be anonymous, and instead be fully recognized for their roles and invaluable contributions as stewards of the Solar Protocol project.

4.5 Thematic Analysis and Codebook

The conversations with stewards were transcribed and varied in length from one to two and half hours. Four researchers on our team engaged in iterative coding and thematic analysis based on a thematic coding process [11], which involved familiarizing ourselves with the data, generating initial codes, identifying for macro and micro codes, collectively reviewing potential themes, re-defining and naming themes, and mapping out the landscape of each solar server steward.

In the initial stages of thematic analysis, our goal was to gain an understanding of the overall motivations, challenges and goals associated with distributed stewardship practices, but as we iterated on this analytical process we became fascinated with also capturing more subtle elements such as personal stories of intermittence, the use of emotional language and metaphors. At least three researchers independently coded each interview and engaged in multiple debriefing sessions to compare, discuss and coalesce around common themes and overarching categories [43, 75]. For the next rounds, two members of the research team further re-coded the data, identifying emerging micro-themes. The researchers also explored the code co-occurrences to bring to light the links between systems, unraveling how often the technological aspects of the project are interwoven with the social fabric of the community. We used this to guide our thematic development.

Dimension	Code & Definition
Stewardship Emotions, relationships, responsibilities linked to being a steward	**Future opportunities** *General opportunities fostered by this kind of infrastructure/system and by the act of stewardship* **Data visualization** *The role of data visualization in supporting stewardship, decision making and broader community engagement* **Care rituals** *Stewardship routine maintenance, checking up on server, care* **Communication** *Communication challenges, opportunities and tools* **Emotional landscape** *Emotions elicited by stewardship* **Relations among stewards** *Connection to other stewards, opportunities to learn, discuss and collaborate together* **Troubleshooting** *Specific mentions to troubleshooting processes as part of stewardship*

Dimension	Code & Definition
Stewards' Identity Stewards' unique profiles, local contexts, backgrounds, motivations & goals	**Situatedness** *Mentions of the unique nature of the context* **Stewards motivations** *Stewards' personal interests & motivations for joining the project* **Goals** *Goals for the experimentation and projects stewards want to develop* **Background knowledge** *Stewards' pre-existing knowledge or previous related experiences*
Learning Mentions of stewards' learning journeys, challenges, opportunities and pedagogical goals	**Experiential learning** *Explicit mentions of tangible, hands-on, experiential learning* **Collaborative learning** *When learning is happening through interactions with others* **Learning goals** *Learning goals linked to engaging with the platform and future projects* **Learning resources** *What actually facilitates the learning, media/tools for learning (e.g. one-on-ones, tutorials, zine, etc.)* **Documentation opportunities** *Ways in which documentation has helped or could help*
Infrastructure Specific mentions of different layers of infrastructure, cyber-physical and human	**Access** *Challenges with, inequity in access levels, access to services* **Institution** *Institutional politics and decision-making* **Networking** *E.g. ISPs, port forwarding, IP addresses, etc.* **Re-imagining** *The act of rethinking, re-imagining relationships with infrastructure/tech*

Dimension	**Code & Definition**
Environment Mentions of ecology, environmental thinking and conservation, climate-related topics	**Environmental Awareness** *Explicit mentions of of environmental conditions, natural rhythms, environmental variables (natural booleans)* **Intermittence** *Challenges and opportunities raised by intermittence* **Low-carbon approaches** *Energy-consciousness and ways of thinking about low-energy tools and alternatives* **Seasonality Opportunities** *Responses to seasonality and specific examples of the impact of seasons*
Community Any mention of the internal Solar Protocol stewards' community as well as external communities stewards want to include or are part of	**External Communities** *Communities stewards want to include/serve moving forward* **Social Invitation** *Ways in which SP encourages experimentation, invites the community in* **Solar Protocol Community** *Why is the SP community important to stewards, what stewards see the values of the community to be* **Sharing** *Sharing with others, sharing of resources, sharing of knowledge*

Table 1. Codebook overview, organized around six main dimensions/themes.

Our analysis resulted in the emergence of fifty unique codes organized around six overarching dimensions of stewardship (Table 1): *Stewardship*, *Stewards' Identity*, *Learning*, *Infrastructure*, *Environment* and *Community*. While not exhaustive or entirely identical across all stewards' perspectives or sites, this codebook gives an overview of the stewards' experiences and can speak to concepts that apply to infrastructural and environmental awareness more broadly. Only the most salient codes are reported below in the interest of relevance.

4.6 Triangulation of Data and Experiences

We triangulated the survey and interview data with multiple additional resources collected over the four years (2019-2023) of the project to ensure a comprehensive understanding of the stewards' experiences. This included researchers' formal and informal communications with stewards, such as emails, text chats, and calls, which provided real-time insights into their ongoing challenges and engagement with the system. We also integrated findings from extensive one-on-one technical onboarding and troubleshooting sessions, both in person and remotely, which gave us a detailed view of how stewards interacted with the Solar Protocol infrastructure on a practical level. Online communications on the project's Discord server further enriched the data by capturing collective knowledge sharing and problem-solving dynamics among stewards. Additionally, we incorporated researchers' observations and reflections, captured through written memos, based on their roles as stewards, system architects, and guides supporting the other stewards. These multiple roles allowed us to contextualize and further reflect on the lived experiences of managing solar-powered infrastructure and compare our own stewardship challenges with those described by the interviewees.

To systematically analyze and cross-reference these diverse data sources, we employed affinity diagramming and clustering techniques [3, 31, 32], which were chosen because well suited to capture patterns across varied, multimodal data sources. These methods allowed us to map recurring themes, emerged from interview coding, onto discussions in email threads, Discord conversations, and researcher memos, helping to validate connections across different engagement modes. By structuring insights through clustering, our analysis of these diverse data sources contributed to a multidimensional perspective on how stewards situate, sustain, and care for their infrastructure within their unique environments.

5 Findings

Our study findings highlight how intermittence shaped the experiences of Solar Protocol stewards, prompting creativity, care and adaptability in their engagement with solar-powered servers. As stewards navigated fluctuating energy availability, they became attuned to the hidden dependencies between solar energy and the broader physical and human infrastructure, making visible the often invisible relationships that sustain digital networks. We have organized our findings around the different types of intermittence and what it made more visible to the stewards. As we move to the discussion we argue for the importance of intermittence not merely as a challenge but as a framework for fostering sustainable practices, promoting reflection on energy use, and rethinking how we engage with technology within the constraints of environmental cycles.

5.1 Intermittence as Epistemological Tool

In our data, intermittence operated across three interconnected dimensions: infrastructural, environmental, and capacity-based. Infrastructurally, it emerged through the constraints imposed by institutional policies, networking limitations, and access restrictions that shaped stewards' ability to maintain connectivity. Environmentally, it reflected the natural rhythms of solar energy, where seasonal shifts and planetary cycles dictated server uptime and resource availability. In terms of capacity, intermittence surfaced in the ebb and flow of human participation, influenced by stewards' time, personal circumstances, and shifting commitments. Through these layers, intermittence serves as an analytical tool, revealing the complex interdependencies within sociotechnical systems and prompting a reconsideration of resilience, access, and sustainability.

5.1.1 Infrastructural Intermittence. By layering the Solar Protocol platform onto existing infrastructures [56] and social frameworks, stewards encountered complex interdependencies and power structures at their sites which in turn affected their participation in the project. The infrastructural intermittence experienced by Solar Protocol stewards made tangible the limitations of access and control within networking infrastructure, exposing layers of gatekeeping imposed by institutions, governmental agencies, and Internet Service Providers (ISPs). These were evidenced in the interviews and captured through codes such as "institution," "access," and "networking," which frequently co-occurred and were further triangulated through multiple Discord threads where stewards shared ongoing challenges navigating networking and institutional structures.

Academic institutions, where several stewards initially attempted server installations, acted as significant gatekeepers. While access to resources and community connections was beneficial, universities also imposed rigid infrastructure controls. Both the research team and stewards across the United States, Canada, China and Chile faced similar hurdles, as each had to navigate their institutions' IT departments and request authorization from multiple authorities, revealing the complex permission protocols and hierarchical structures governing connectivity at these institutions.

> *"... the IT (department) seemed to be down with it and then my professor told me just don't worry about it anymore. It's part of our school now and they can't stop you."* - **CS**

Nodes installed at universities were also intermittent and frequently disconnected by administrators for privacy concerns or maintenance, requiring time to retrace steps and navigate institutional channels to restore access. For example, infrastructure or building maintenance caused prolonged and unexpected downtime, often beyond the control of both stewards and researchers. For one steward, the university's decision to remodel led to the server being "down" indefinitely.

> *"Initially, I put the work in two exhibitions I curated in 2021 and decided to keep hosting it, although it has to be taken down till now, the university is remodeling that area. Hope to bring it up again in a month or two."* - **BC**

As a result, universities proved to be one of the most challenging environments for solar-server installations, leading many stewards to ultimately relocate their servers to their homes.

> *"Still at my home. Yeah. I ended up not getting permission to put it on the roof or attach it to a building, the panel, and then like figuring out the wiring, it seemed unlikely that I was going to be able to run a wire through a wall or permanently have a window open in the Canadian winter. So yeah, it has been a very domestic thing for me."* - **AP**

Even when stewards were able to successfully install their servers at home, where they had more control, they faced friction in trying to access the networking port needed on their routers for the server to communicate to the outside world. This usually required dealing directly with the local Internet Service Provider (ISP) and its tech support teams. ISPs very much created an additional layer of gatekeeping that stewards had to intimately familiarize themselves with in an effort to open pathways for their server to join the broader Solar Protocol network (Fig. 5).

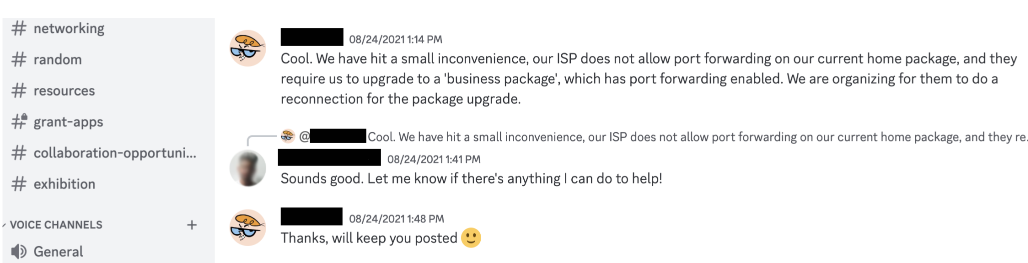

Fig. 5. An example of ISPs' gatekeeping actions from a stewards' chat

It was a surprising and illuminating discovery to see every single steward face challenges in interacting with ISPs across the Globe as well as the lack of consistency across different ISPs, which made stewards acutely aware of their peculiarities.

> *"It was up and running, there were some challenges with my moving and then changing ISPs, so I had to sort of like redo some of the set up a couple of times, which involved learning different things about different Internet providers and their eccentricities."* - **AP**

Stewards had to resort to a number of workarounds and ad-hoc solutions such as installing their own networking hardware to claw back as much access and control as possible, or negotiating with and contracting separate ISPs to install dedicated networking connections for their self-hosted server:

> *"My main home network is separate from ... I have two connections. One's having the protocol. One's just for my house. The idea was to figure out how to just have one, but I think I am just very afraid of the networking issues because again it gave us a lot of headache last time."* - **DW**

Custom workarounds were also necessary in certain contexts due to government policies restricting access to Internet services or equipment. For one steward, obtaining legal ownership of the equipment needed for its Internet infrastructure to be updated was a huge hurdle. What they define as a "long story" encompasses many months of bureaucracy that prevented the server from joining the network, shining a light on the inefficiencies of government-run infrastructuring projects, especially in underserved areas in the Global South [21]:

> *"I have some equipment here, but I'm still waiting for... Well here we always have a long story handing over, and all that story. I have some equipment here, but I cannot use them yet. But when it's handed over officially to me, one of those pieces is it's a gateway for the network."* - **SJ**

SJ's local government's decisions to upgrade some of its physical infrastructure also led to compounded infrastructure failures:

> *"I have a link set up to my home, but the area that has the hub, it's supposed to be on solar, but the solar is down. We're using the grid, but then the grid was turned off because there is some work they're supposed to start on the building. So that's kind of happening."* - **SJ**

Other governments, such as China, censor both the publishing and viewing of online material to control the flow of information, limiting access to content deemed sensitive and preventing the dissemination of unregulated media. One steward had to find creative solutions and rely on ad-hoc support to bypass these restrictions. Due to this government censorship, the steward struggled to connect their node, raising broader conceptual and sustainability concerns.

> *"To have it working behind firewalls, I sorted it out using Frp*[1]*. However, it brings about conceptual challenges as Frp involves a middleman server, which is not solar powered."* - **BC**

In several cases, Solar Protocol's intermittent infrastructure was in fact layered onto existing patterns of intermittence. This manifested in unreliable connectivity, as stewards described how systems would ebb and flow due to ongoing infrastructuring efforts [22]. Unfortunately, in three cases where servers were reliant on other unreliable technical or human infrastructures, these extended periods of hiatus caused the servers to more permanently drop off the project.

> *"Yeah the Internet is okay. Just that we are still working on setting up the network to be more consistent. Right now we still have little, little, little... No, I mean it comes and goes sometimes, certain areas drop off at certain times because we are still putting up nodes and we are still replacing older equipment with newer ones... "* - **SJ**

These exchanges across separate layers of institutional and governing bodies illuminated how seemingly open and accessible technological platforms, in reality, are shaped by layers of strategic gatekeeping. The process of self-hosting, while appearing autonomous, is heavily regulated and requires navigating complex bureaucratic and infrastructural constraints. These tensions deepened stewards' understanding of the forces governing their ability to fully participate in the project, and forced them to negotiate alternative ways to engage with the platform:

[1] https://github.com/fatedier/frp

> *"... as I contemplate what it would mean to do sort of like traveling public stuff, this is something I'm pondering. I'm not sure if it will be feasible to stick with Solar Protocol because of the kind of constant updating ISP issue. Maybe I just get a SIM card that I can hook into something and that works. {...} But one sort of open question that we have in the future is if we're going to sort of take it on the road and try and do some public installations with it, how mobile it will be and how easy it will be to reconfigure the port forwarding, is a challenge for the future."* - **AP**

Several stewards were in fact inspired to make their solar servers mobile, aiming to bring them into their local communities to foster engagement in new ways. However, these efforts quickly highlighted the fragility of wireless networking and exposed broader infrastructural constraints. These direct encounters with infrastructural boundaries provided stewards with critical insight into the layers of control embedded within digital networks, underscoring the impact of intermittence on adaptability and access. Finally, this infrastructural understanding pushed stewards to think critically about how future projects might need to navigate and overcome these constraints in order to expand their reach within their communities.

5.1.2 Environmental Intermittence. The rhythms of the Sun, shifting seasons, and passing clouds shape the life of Solar Protocol's servers, making environmental intermittence a fundamental force that governs their uptime and availability. Additionally, in regions of the Global South, infrastructural intermittence is deeply shaped by environmental cycles, rendering stability fragile and often already contingent on seasonal rhythms. [30, 72]. One steward described this experience of already intermittent connectivity:

> *"Nothing here works consistently ever. Everything ebbs and flows, everything's on or off. I mean the Internet used to stop here every time it rained for many years. Every time it rained it would just go down."* - **CB**

By tying its energy source directly to the Sun, the Solar Protocol platform and its servers were intentionally designed to draw an even more explicit connection between the functioning of the system and the environmental conditions that drive it. We found that its intermittent nature attuned server stewards to both local and global environmental rhythms. To begin with, seasonal changes caused tangible fluctuations in the energy available for server computation, as one steward pointed out:

> *"In the winter, it was pretty common for it to go down every other day, if it was pretty cloudy."* - **AP**

Engaging with the platform by hosting content during months of limited sunlight resulted in practical challenges, as this steward experienced intermittent visibility of their public content due to the periods of limited sunlight and, therefore, energy scarcity. We observed this issue reflected in a rise in one-on-one troubleshooting calls, as stewards sought guidance to adapt to the constraints posed by seasonal light availability. As one steward reflected on their use of the server to host content for a workshop at an academic conference:

> *"So the call for papers for the CHI workshop for instance, was posted on the winter solstice, like the worst day of the year for it to be on this Northern server."* - **AP**

Needing their content to be available at a particular time cued this steward into specific celestial events that influenced the energy production, and therefore the server's performance. In other instances, these natural "shifts" from scarcity to opportunity, made the fluctuation of solar energy availability tangible in ways that could support creative thinking about resource use and public engagement.

> *"Because, yeah. It's summer. Pretty much every day, there's these periods where we hit a hundred percent battery and just have excess to spare. And so, finding something interesting to do with that and finding a way to communicate the pleasures and then also environmental bargain of this to the public is, I guess, the next open question."* - **AP**

Exploring the system's solar data through data visualizations was mentioned by this steward as a clear opportunity to crystallize further this seasonal awareness obtained experientially by living with their server over a period of time:

> *"Part of the hope of being able to do data visualizations is to get a clearer picture of what I've intuited through the cycle of living with this machine, but seasonality looks pretty significant here in Canada."* - **AP**

Weather dependency and the inherent constraints of solar energy encourage an awareness of energy use, conservation, and resource-sharing, linking their efforts to a broader sustainability ethic that resonates uniquely with each steward and their server's geographical and social context:

> *"And I think this is just a really rich place too, for thinking about what collective resources mean and sharing, and not taking more than you need, and living within your means and being sustainable."* - **CB**

The intermittence of the system, in fact, prompted stewards to want to leverage their energy usage further:

> *"I'm actually quite curious what the impact of that is on the energy draw on the battery. It would be interesting to throw that weight around a little more obviously and test what the system can do."* - **AP**

The inherent limitations of solar energy heightened stewards' awareness of resource constraints within their local infrastructure, an aspect often obscured from the end-user. This led to a growing interest in conducting energy audits to reduce ecological footprints and optimize energy use:

> *"Trying to find a way by using the Pi computing power to offset, at least some part of, the environmental impact from the panel and battery."* - **BC**

> *"Just how can you be able to build small computing units that are powerful and also energy efficient?"* - **DW**

By embracing intermittence, stewards attuned themselves to environmental rhythms, fostering reflection on the ecological constraints and affordances of technological systems. Through daily engagement with fluctuating energy availability, they developed an awareness that extended beyond observation, inspiring sustainable practices in their own lives.

5.1.3 Human Capacity Intermittence. Participation in Solar Protocol was shaped by the natural fluctuations in stewards' availability, underscoring time as a critical but limited resource in sustaining collaborative infrastructures. This ebb and flow of involvement was further compounded by logistical constraints such as temporal differences, scheduling conflicts, and shifting life circumstances that required relocation or changes in priorities. The stewards, in fact, engaged in intermittent patterns of communications, often increasing in intensity during the early stages of a server build or when troubleshooting was required. This pattern was particularly noticeable in the two most active Discord channels, #networking and #hardware, as well as through email and text messaging when they would reach out for help.

> *"I feel like once someone sets up their platform, the question is usually around, 'Hey, how do I do this? Oh, this wire goes where?' Whatever. Once that is done, usually just goes silent."* - **DW**

Stewards balanced multiple responsibilities, including academic, professional, and personal commitments, therefore leading to periods of high activity followed by lapses in engagement.

> *"And yeah, when we actually get in striking distance of those technical problems, we'll be sending you some emails, asking some inquiries."* - **AP**

The distributed nature of the project across multiple time zones made real-time communication very challenging, as we were unable to have all stewards attend any live events. This limitation prompted us to rethink how to collaborate in a more asynchronous manner, ensuring participation and knowledge-sharing could occur despite temporal differences:

> *"I'd love to chat, but when we discuss time slots to chat, it came to me that it is in the nature of this project, everyone is in different time zones, so I guess email is good."* - **BC**

One steward expressed the need to temporarily "unplug" from mainstream Internet by disconnecting from some of the social media platforms we had been using to keep in touch and provide more just in time technical advice, possibly making communications less timely:

> *"And along the way, I'm disconnecting from mainstream social media. So, not on Instagram, very minimal on Facebook, not on Discord."* - **CS**

Time availability was the most critical and intermittent resource in stewarding the servers and the project as a whole, as our own experiences as maintainers of the Solar Protocol also demonstrated. One steward noted that their part-time schedule allowed them sporadic opportunities to monitor their system's health:

> *"It is at my college, so I'm not checking in on it every day, which is why every once in a while, I was trying to check... Is the site up?"* - **CS**

For all stewards, the commitment to maintaining and repairing the infrastructure was an additional responsibility on top of their personal and professional obligations, often competing for their time and attention. One steward, for example, mentioned that the server was installed at a community-based organization they were also responsible for running, leaving them little time to experiment with the platform. This challenge led them to consider relocating the server to their home, to separate it from their daily work duties.

> *"Yes, I'm thinking of moving it to my home because that would give me I guess I would say more leeway, more time with it. Because here at the office, I only come here during the day and during that time I also have to work, so my time with it is limited. But if I have it at home on a weekend, I can do some stuff on there. When I get home in during night, I can also do some other stuff on that. That would give me more time with it. So move it home, that'd be better."* - **SJ**

It became apparent, engaging with stewards over time, that people's lives are naturally intermittent. Whenever a steward relocated, their server would go offline, temporarily or permanently, contributing to the overall intermittence of the Solar Protocol platform, further emphasizing the dynamic and fluid nature of participation in the network (Fig. 6).

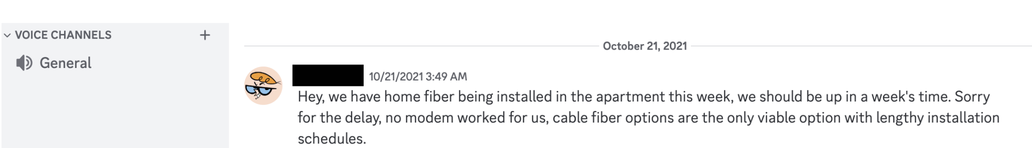

Fig. 6. A chat with a steward re-installing their server after moving

As researchers managing the platform, we witnessed stewards uprooted by new professional opportunities and personal life shifts like new relationships and breakups, prompting servers to be uninstalled, packed, and relocated. Likewise, students who had nurtured Solar Protocol through their studies graduated and moved on, often leaving their servers behind, remnants of their time and care embedded in institutional spaces. This frequently resulted in servers going offline for unpredictable periods until new stewards could be assigned. This underscores the delicate synergy between the technological layer and the human layer of shared infrastructure, as well as the need to design systems that accommodate and are designed with fluctuating participation, without compromising infrastructure resilience.

5.2 Intermittence as an Invitation to Stewardship

Several of our stewards developed a deep emotional connection with their systems, nurturing them through personalized care. To better understand how they reflected on their role in the project and their evolving relationship with the servers, we examined the affective language they used to describe their experience [63]. These words capture the stewards' unfolding journey, reflecting their growing commitment to stewardship and the learning process it entails. Descriptors like *"Bonded", "Care", "Affective", "Maternal"*, and "*Fuss*" reflect the strong relationship they were building with the servers, while terms such as *"Grateful", "Consolation", "Sad", "Hope", "Enthusiasm", "Fun", "Edifying"*, and "*Motivating*" highlight the emotional highs and lows they navigated. Together, these words reveal a spectrum of experiences that shaped their engagement and growth, from nurturing bonds to moments of frustration and fulfillment.

For instance, one steward expressed how intermittency created a sense of safety and refuge from the always-on nature of mainstream Internet platforms, stating:

> *"The notions of information and privacy, but also the idea that I have a very strong relationship with the Internet, but a lot of that has trauma associated with it. And that just because I'm very online doesn't necessarily mean that I want to be on these mainstream forms of Internet."* **- CS**

Intermittence shaped the repetitive and continuous nature of the maintenance routines, which emerged from the interviews and Discord conversations as providing emotional structure and continuity for the stewards. Small acts take on affective significance as they become part of the stewards' daily habits. This regularity fosters a long-term bond with the system, as it becomes embedded in their daily lives:

> *"So I am constantly updating it and have these little rituals of maintenance, both on the software side and then also on the hardware side [...] that my experiences as a steward have been in that kind of like maternal mode. Like, I enjoy fretting over my server."* **- AP**

These interactions transform into meaningful practices that go beyond mere upkeep and reflect a personalization of the server, treating it as a companion, something to nurture and care for, not just a technical tool. The intermittent nature of these servers and their environmental dependency, foster a particular kind of stewardship, one that requires ongoing care, maintenance, and emotional investment. Seasonality also offers an opportunity for more focused acts of care (Fig. 7).

Rather than focusing solely on repair when things break, stewardship under intermittence involves a continuous engagement with the system's fluctuations, fostering a deeper sense of responsibility and emotional attachment. This more "care-full" [85] approach, exemplified in small acts of routine care, like repositioning solar panels or cleaning them (to extend server uptime), fostered a continuous connection for one steward:

> *"So I would have these little morning rituals where I would bring my solar panel slightly out from one corner of my deck where it will get more morning sun and then move it*

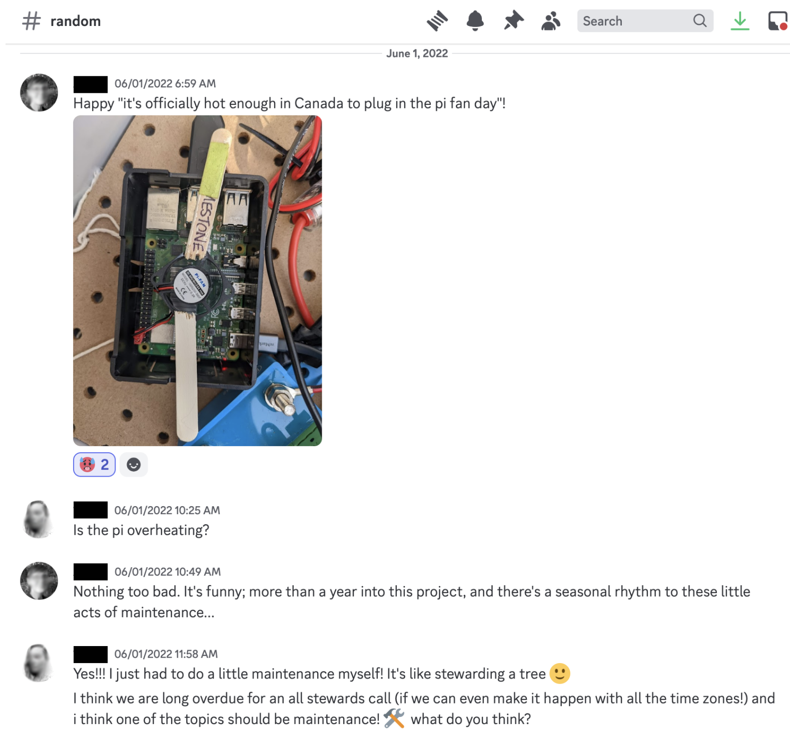

Fig. 7. A chat conversation about seasonally-prompted acts of server maintenance

> *further back into the sunny spot in the afternoon to try and keep it alive a little bit longer. Or like washing down the panel, that kind of stuff. And like these are, to a degree, slightly absurd acts, I think I haven't bothered to quantify and therefore more precisely know the extent of this intervention. On like the uptime or anything."* - **AP**

The "slightly absurd" nature of these acts, which go beyond repair and maintenance, reflects the personal satisfaction and meaning stewards derived from caring for the system in small but significant ways.

> *"But this is just to say that like my server and I are fairly bonded and kind of vibe together in these sorts of small quotidian ways. And yeah, I like caring for it. And there's something about that, that to me defines what this experiment has meant. And yeah, what one learns by doing so. Like, stewarding is a good word, but like also, maybe doesn't quite go far enough to like tap into this affective thing that's happening."* - **AP**

As a platform and infrastructure in a constant mode of 'becoming' [39], stewarding a Solar Protocol intermittent server required a muscular lift encompassing the constant learning of its technological, social, and environmental infrastructures while acquiring the necessary skills for troubleshooting and repair. As SJ reflected:

> *"It's a learning experience for me. I'm learning, and then I'm actually doing."* - **SJ**

As stewards learned more about the system through hands-on involvement, they identified how they developed both technical skills and a personal attachment to the machine. The act of learning through care transformed the relationship into something more than just a technical task, leading to a sense of accomplishment and emotional satisfaction. Yet, the emotional investment in stewardship was not without its challenges. Due to varying access to resources and infrastructure, some stewards found themselves needing one-on-one troubleshooting sessions to overcome technical issues, which often required time-intensive, individual support.

> *"And you gave generous many hours to helping me troubleshoot things and getting it up and running."* - **AP**

The interviews also capture a strong negative emotional reaction to the potential or actual failure of the system. AP describes feeling consoled by data visualizations when the battery is about to die, indicating that these technical failures elicit a sense of sadness or loss as stewards began to develop an affective relationship mediated by the system's uptime and downtime.

> *"So, at my most ambitious, this would involve somehow fitting a pen plotting machine into the NEMA case or into a second NEMA case that just sits next to it, such that either when the battery's about to die, it draws a picture that visualizes all of the data since it last went offline. And then I feel less sad."* - **AP**

This raises some interesting questions around what parts of the infrastructure are visible and should be visible to the stewards at any given time, especially when considering the system from the perspective of stewardship and server maintenance practices. Having more explicitly visualized data about the overall health of the system would be helpful in supporting stewards' infrastructural awareness as a way to better inform the care practices for their servers.

> "*This does come from a kind of emotional place, right? Like, oh my server is dying, but I have this consolation that is also a useful infographic, indexing how it's been. And so I can fuss over it with greater empirical acuity."* - **AP**

Given the burdens of individualized stewardship, many stewards felt that having access to a community network could help alleviate some of these challenges. Instead of relying solely on individual support, a community-based model could enhance sustainability and distribute the workload.

> *"It would be really nice to kind of have a figurative board full of lights that turn on when different people complete their tasks. Just to kind of get a sense of, yeah, us being together on more than just Zoom."* - **AP**

The affective relationships that stewards developed with their solar-powered servers seem to emerge from a combination of personal investment, ritualistic care, learning, and creative experimentation. Through the lens of "caring with" [82], stewarding these systems extends beyond technical tasks to encompass a relational, human-centered approach to digital and environmental stewardship. Integrating these servers within active, supportive communities could foster collective resilience, reinforcing the socio-ecological consciousness that Solar Protocol aims to cultivate.

5.3 Solar Protocol as Infrastructuring

We found that the infrastructural inversion [9, 78] of Solar Protocol, which makes the infrastructure visible by placing stewards in direct engagement with its operation and constraints, fostered new imaginaries for ecologically focused projects and interactions. Stewards engaged creatively with the platform, with some experimenting with low-carbon research methods or envisioning off-grid, climate-resilient archives of local knowledge. The Solar Protocol platform, which embedded intermittence as a core feature, challenged the assumption that always-on, seamless connectivity is the ideal state, and prompted stewards in critical reflections.

> *"And then getting into questions of, 'Why do we have so many things that are on all the time through the night, even when people are asleep and what does that actually accomplish? And who does that serve?'"* - **CS**

As stewards learn to navigate intermittence, they are actively engaged in re-infrastructuring their relationship with technology, forming new habits, routines and values around care. As a framework for design, intermittency, compels the stewards to rethink conventional infrastructural norms that prioritize constant uptime and stability. This contributes to the stewards' need for re-infrastructuring, where systems are designed or reconfigured to accommodate variability in power, connectivity, and performance. We captured these re-infrastructuring moments through the codes "re-imagining", "future opportunities", and "low-carbon methods". SJ, for example, connected to intermittence the opportunity to host local youth media production (photographs, songs, videos) and other artifacts from various local Indigenous cultural groups. The server was seen as a space that could host and support the broader community's set of wants and needs, particularly in cases where communities experience intermittent access to the broader Internet.

> *"But with the Solar Protocol, that server we can store stuff online, I can advertise it on different websites. And it makes it easy because it's not being run by any agency, it's being run by me... I can afford anyone the opportunity to put anything on it or save anything on that, to broadcast anything on it, you know what I mean? Why not?"* - **SJ**

Most stewards' thinking positioned the server as a form of "commons" [19], a shared public resource [39] that should be extended beyond the individual steward. SJ's emphasis on creating local media archives that are accessible to everyone shows a process of re-infrastructuring.

> *"With that local network and if we have the server hooked up on there, you would have stuff saved on there that you can still access, you can still share with each other, you can go back and look, you can read something online from the server, that kind of thing. [...] If I have the council hooked up on there, the school hooked up on there, another person or other smaller or groups in the community hooked up on there, then they share stuff and then everybody can access it."* - **SJ**

SJ situated his intermittent infrastructure in a landscape of possibilities set against the backdrop of intensifying hurricane seasons in the Caribbean. By setting up this server SJ hopes to re-design future infrastructure to allow the community to still access meaningful resources and content even during emergencies. Re-infrastructuring under an intermittent framework stimulated stewards to re-imagine, for example, more decentralized networked systems:

> *"... How can we be able to create these decentralized technologies and users can be able to create their own form of "projects" and host on the platform, and it can run independently of a centralized server."* - **DW**

Designing for fluctuating conditions led stewards to engage in re-infrastructuring, where infrastructure is shaped not solely for efficiency or performance but for alignment with sustainable, low-energy, and environmental principles.

> *"The experience shifts from scarcity to abundance is also really motivating our desire to produce art based on the data and infrastructure [...] And then from that idea sprung the obvious [...] which was to set it up so that whenever there is a hundred percent power on the battery, it's just constantly turning out something. Visualizations of maybe the past 72 hours or maybe that "since last turned off" thing and that would get pretty long as the summer goes on."* - **AP**

AP's idea of intermittently powered art, informed by solar energy, envisions a re-infrastructuring grounded in more sustainable practices. The intermittent nature of Solar Protocol's infrastructure opened up space for stewards to extend their digital experiments into their communities inviting others to interact with sustainable computing models.

> *"So it has been this kind of social invitation in a way, right? Like Solar Protocol as a network is a platform, but like my little server is also a platform for people who want to do things and host things and sort of experiment with knowledge exchange with this modality, this sort of low energy, low file size, potentially intermittent mode of networking, which is really, really fun and great."* - **AP**

The stewards did not see the infrastructure's limitations, such as low energy and file size constraints, as drawbacks but as features that stimulate creative approaches and community interactions.

> *"Visualizing that data, creating kind of like Boolean state actions for peripherals, like a drawing bot and just otherwise finding ways of sort of bringing the project out of my backyard and into the public a little bit more where I think it'll be really, really interesting and provocative for different forms of projects, some in the arts sphere, some in the more science communications sphere and some just as a way to connect with fellow environmental computing nerds."* - **AP**

By visualizing data and connecting their solar servers with public activities, stewards like AP, SJ, DW and BC moved beyond their individual practices and opened pathways for others to interact with and reflect on the environmental implications of digital infrastructure. BC, in fact, emphasized how situating this project on a university campus can serve as a way to encourage students to think critically about the thorny relationship between sustainability and technology:

> *"Young minds are sometimes tied up with what's going on around them, AI, NFTs, deep space, but pay less attention on our spaceship Earth, so keeping this project on campus is a way to remind them about computing cost energy and has great impact on environment, hopefully develop interests on broader environmental topics."* - **BC**

Stewards like SJ, AP and CB effectively integrated intermittence into their thinking, planning for disruptions and incorporating it into creative and practical uses of the system (e.g., emergency communication networks, intermittent art production, educational resource). By foregrounding intermittence, the stewards engaged with resilience, sustainability, and appropriate technology, aligning system and project design with the natural rhythms of solar energy and broader environmental factors.

6 Discussion: Intermittence as a Feature, Not a Bug

Historically, CSCW research has been concerned with infrastructure reliability and continuity, often emphasizing seamless access, efficiency, and stability [9, 33]. Our findings, however, reveal how intermittence can function as a generative design condition: one that exposes hidden dependencies, fosters adaptive strategies, and deepens engagement with infrastructure. Intermittence, as conceptualized by Liu [44] and further explored in this study, offers a framework for rethinking infrastructure resilience, particularly in contexts where continuous access cannot be guaranteed. Our work on Solar Protocol builds on Aoki et al.'s identification of tensions and trade-offs in sustainable infrastructure [2], expanding their design considerations to position intermittence as an inherent condition rather than a flaw. This reframing is particularly relevant in infrastructuring efforts in resource-constrained settings, such as decentralized networks in the Global South [22, 55, 72], where infrastructural instability is an ongoing reality. Our research illustrates how Solar Protocol stewards navigated and leveraged fluctuations in power and connectivity, engaging more deeply with the environmental, technical, and social dimensions of their systems. The infrastructural barriers stewards faced, including navigating institutional policies, ISP restrictions, and bureaucratic hurdles mirror challenges in other community-led digital infrastructures. Similarly, environmental intermittence highlights broader sustainability concerns, as energy availability and climate disruptions increasingly dictate system design and operation. Finally, intermittent stewardship underscores a fundamental challenge in participatory projects: the ebb and flow of engagement due to personal, professional, and logistical constraints.

However, our findings also highlight that intermittence is not universally navigable; its impact is shaped by structural constraints, power dynamics, and existing infrastructural conditions. While in some cases, intermittence encouraged creative adaptation and ecological attunement, in others, institutional gatekeeping and networking barriers rendered it an obstacle to participation. Rather than treating intermittence as an issue to be universally solved or celebrated, we argue for a more nuanced approach: identifying when and how intermittence can be leveraged as a design feature, and when its structural constraints require more substantial intervention. By doing so, we expand discussions on sustainable infrastructure, offering additional perspectives on designing for resilience within systems that inherently operate under fluctuating conditions.

6.1 Navigating Structural Barriers to Access

Our findings revealed the structural and institutional dynamics that regulate access to technology [9]. Stewards' experiences navigating institutional policies, ISP restrictions, and bureaucratic barriers highlighted how seemingly open infrastructures, in reality, are shaped by layers of gatekeeping, permissions, and policy constraints. The intermittent failures and disruptions they encountered exposed the political nature of infrastructural control, revealing the hierarchies that dictate access. These challenges forced stewards to confront foundational questions about power and governance in technology: *Who owns your infrastructure? Who dictates your access? What systems of control operate beneath the surface of everyday connectivity?* By grappling with these tensions firsthand, stewards gained an embodied understanding of how authority, policy, and regulation shape technology, an essential awareness for those seeking to build alternative or community-driven infrastructures.

Prior CSCW work has explored how infrastructure is embedded in social and institutional structures, often reinforcing hierarchical power dynamics and exclusionary access policies [37, 78]. Our findings extend this research by showing how intermittence itself makes these structural entanglements tangible for those navigating infrastructural barriers. The constraints stewards faced ranged from navigable to insurmountable, shaping the kinds of design interventions that might support more flexible, adaptive engagements with infrastructure. Opportunities for design arose in cases where movement, both physical and technical, was possible. This includes supporting more flexible relocations, enabling stewards to move their servers to sites with fewer institutional restrictions, and designing for easier transitions between providers when connectivity barriers emerged. We also identified cases where design could assist in advocacy, helping stewards push back against restrictive institutional policies, negotiate with IT departments, or navigate overall opaque ISP regulations. However, some barriers such as government censorship or widespread infrastructure failures were beyond the scope of design interventions alone. In such cases, intermittence as a feature is only viable with substantial resources and external support.

These findings highlight a critical question for CSCW: *How can design help users navigate constrained infrastructure and develop solutions within the limits imposed by institutions and service providers?* Research on community-owned networks, alternative infrastructures, and policy-aware design offers valuable pathways for addressing these challenges [53, 55, 72]. Understanding where design can meaningfully intervene, and where deeper structural change is needed, remains an essential challenge for sustainable and just infrastructuring efforts.

6.2 Synchronizing With Natural Phenomena

Unlike infrastructural intermittence, which exposed constraints shaped by institutional and policy-based dynamics, environmental intermittence cultivated a different kind of engagement tied to natural events. This included both predictable cycles, such as daily sunlight availability and seasonal shifts, and more erratic fluctuations, such as cloud cover and extreme weather events. Stewards not only adapted their behaviors to these environmental fluctuations but also developed an embodied awareness of planetary cycles.

In cases of more predictable intermittence, such as daily and seasonal solar availability, stewards learned to align their expectations and usage patterns accordingly. However, misalignment between their infrastructural needs and environmental constraints sometimes led to challenges such as needing content to be available when energy was scarce, or encountering unexpectedly long periods of cloud cover that disrupted uptime. In some cases, environmental intermittence compounded infrastructural intermittence, as storms and power outages took down Internet connectivity, making system downtime not just an issue of solar power but also of broader infrastructural fragility. Rather than perceiving intermittence as a purely negative constraint, stewards also recognized the shifting states of abundance and scarcity inherent in solar-powered infrastructure. When energy was plentiful, there were opportunities for creative engagement, as one steward described planning data visualizations that would only generate when their battery reached full charge. This suggests that designing for intermittence should account not only for constraints but also for moments of surplus, making both scarcity and abundance meaningful in system use.

Prior sustainability-focused CSCW research has explored how technological systems can be reoriented to align with natural cycles [5, 54]. Our findings extend this conversation by emphasizing the importance of attuning human practices, not just technical systems, to ecological constraints. Rather than designing infrastructure to resist intermittence, our study highlights the value of designing for alignment with environmental fluctuations. In fact, experiencing these cycles firsthand fostered stewards' infrastructural learning-through-experience, mirroring prior work on infrastructural inversion [9], where breakdowns expose hidden dependencies and serve as epistemic tools. This awareness not only influenced stewards' immediate engagement with the system but also shaped their broader perspectives on computing and sustainability. Our study suggests that designing with intermittence in mind can serve as an ethical design approach, prompting practitioners to integrate ecological cycles into technological systems [23]. By supporting seasonal and environmental responsiveness, CSCW research can move toward designing infrastructure that is not only resilient but also dynamically attuned to planetary rhythms [39].

6.3 Supporting Intermittent Stewardship

Labor and capacity intermittence pose a significant design challenge. The relational "embeddedness" of infrastructure highlights how systems are shaped by the social practices within which they operate, as Star and Ruhleder argue [76], emphasizing the need for platforms that account for the inherently variable nature of community engagement. Prior CSCW studies have explored how volunteer-driven and community-maintained systems navigate participation ebbs and flows [7, 65], emphasizing that resilience is not about constant availability but rather the ability to sustain engagement despite fluctuations. The availability of stewards was often unpredictable, shaped by shifting life circumstances, professional transitions, and personal responsibilities. These patterns reinforce prior work showing that volunteer participation in community infrastructure is rarely linear or continuous [14].

Designing for intermittent stewardship could involve supporting mechanisms for more fluid role transitions, enabling stewards to hand off responsibilities when they relocate or become unavailable.

Designing intentional pathways for stewardship succession, such as documented processes for transferring responsibilities, could help alleviate these disruptions. In addition to role transition, designing for flexibly distributing participation could have the potential to create collaborative systems that allow for cycles of engagement and dormancy as equal forms of care, without compromising more long-term resilience. A shift in design focus from individual responsibility to collective care could help normalize intermittent engagement by enabling things like shared maintenance practices, lightweight communication channels for re-engagement, or cooperative models of stewardship that distribute labor across a broader network. Intermittent stewardship does not inherently threaten resilience, but rather inspires a rethinking of how participation is accommodated within sociotechnical systems.

6.4 Learning Through Small Acts of Care

In an era of increasing ecological and technological uncertainty, actively engaging with infrastructure through hands-on stewardship is not just valuable, it is essential. One of the most striking findings was how intermittence fostered care-driven interactions. Unlike infrastructures that remain invisible until they break down [33], Solar Protocol's consistent intermittency encouraged routine maintenance, deepening stewards' engagement with their systems. CSCW research on maintenance, repair, and care labor [15, 82] underscores how small acts of upkeep cultivate both infrastructural knowledge and emotional connection. Our findings suggest that learning through maintenance, rather than reacting to failure, enabled stewards to develop a more intuitive, tangible understanding of their systems and the ecological conditions shaping their operation. This raises important design questions: *What if we designed for care rather than efficiency? How can infrastructures support slow, routine maintenance instead of reactive, crisis-driven interventions?* Our findings call for a shift toward stewardship-oriented approaches that prioritize reflection, long-term engagement, and care-based labor [33]. Echoing Liboiron's model of moving from awareness to relational understanding [41], intermittent interactions with solar-powered infrastructure nurtured a form of stewardship attuned to environmental rhythms.

However, the form and context of stewardship shaped stewards' ability to maintain care practices. Those volunteers who maintained servers in their homes developed routine maintenance habits and stronger emotional bonds with their systems but often lacked external support. Conversely, stewards who positioned their servers as shared, community resources in more public settings envisioned fostering collective responsibility but struggled against institutional barriers to connectivity and infrastructure integration. This tension between the autonomy and intimacy afforded by domesticity and the need for shared responsibility highlights the importance of designing for more flexible and distributed community management structures. This interplay between personal stewardship and communal responsibility suggests a need for infrastructure that can hold both: spaces where care can remain intimate, routine and hands-on, yet also branch outward, woven into broader networks of support and shared responsibility.

7 Conclusion

This study on the stewardship of experimental and environmentally responsive infrastructure advances CSCW research on the complex sociotechnical relations embedded in infrastructuring [12, 38, 52, 56] and the collaborative construction of technological systems [7]. Recognizing intermittence across infrastructural, environmental, and human layers offers a pathway to infrastructures that work with, rather than resist, the shifting realities of technological and ecological change. By positioning intermittence as a design feature rather than a limitation, we invite a re-imagining of infrastructure that is flexible, sustainable, and responsive to evolving uncertainties. From decentralized and off-grid community networks to disaster-responsive technologies, designing with intermittence in mind can foster more context-adaptive, care-oriented systems that challenge 'always-on' assumptions and promote sustainability. Our findings suggest that designing for intermittence, rather than against it, while centering existing limits as tenets, can inform a rethinking of resilience and more flexible and sustainable technology-mediated collaborative systems beyond this specific study. Integrating these dimensions into design processes expands the potential for technologies that not only endure but actively thrive within intermittency, contributing to CSCW's broader inquiry into sociotechnical resilience.

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