Open-Source Software, Fediverse and Custom ROMs as Tools for a Sustainable Internet

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Open-Source Software, Fediverse and Custom ROMs as Tools for a Sustainable Internet

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***Abstract*—The transition to sustainable electronics necessitates both resource conservation in hardware production and shifts in software usage. This paper investigates the contribution of Free/Libre Open-Source Software (FLOSS) towards fair, and conflict-free practices through promoting collaboration, transparency, and resource accessibility. Our study investigates how the adoption of decentralized online social networks (DOSN) like Mastodon (microblogging) and PeerTube (video sharing), which operate on the ActivityPub protocol, contributes to sustainable practices within the electronics sector by fostering a federated universe (Fediverse). It is demonstrated how FLOSS, in the form of Alternative Mobile Operating Systems (AMOS) including Android open-source custom ROMs or mobile Linux systems, gain traction due to enhanced privacy protection, improved usability through tracker-free software and alternative app stores, and adherence to EU directives on the right to self-repair. As AMOS mature for everyday use, they attract consumers, thereby contributing towards sustainable electronics development. Furthermore, the Fediverse's Application Programming Interfaces (APIs) enable seamless information exchange between instances, allowing for nuanced moderation that safeguards user privacy. This approach contrasts with centralized commercial networks, where algorithm-driven operations often prioritize profit over user well-being.**

***Index Terms*—sustainability, FLOSS, decentralized, alternative mobile operating systems (AMOS), Fediverse**

I. Introduction

Electronic devices, particularly smartphones, form the basis of many aspects of today's society. Data from 2020 show that approximately 1.5×10^9 smartphones (representing a potential value of $\$1.5 \times 10^{11}$ entering the market) were sold that year, which is consistent with previous trends [1]. By March 2023, approximately 6.92×10^9 individuals worldwide were utilizing smartphones [2]. Here, Google's Android operating system held a global market share of 74 % in 2020. Smartphones' high greenhouse gas emissions mainly stem from data storage in data centers, mobile data traffic and manufacturing, the latter accounting for over 80 % of their life-cycle impact. The need for more sustainable practices arises due to ecological and societal harm resulting from these technologies [3].

Concerns about the short lifespan of devices have persisted for years because Smartphones come with significant challenges regarding sustainability and negative environmental impact, especially concerning how these devices are produced and used. Obsolescence (material, functional, psychological, economic), a major issue in electronic devices, contributes significantly to concerns of sustainability due to its impact on e-waste generation and shortened product lifespans driven by rapid technological advancements rendering them less useful or irrelevant over time [11]. Therefore, LCA (Life Cycle Assessment) was applied as a valuable tool that assesses potential risks for obsolescence by examining technological trends and market conditions. Due to this significance, the European Commission has established a European Platform on Life Cycle Assessment to address these concerns and serve as a tool for promoting sustainable practices [4]

E-waste directly impacts the environment by increasing e-waste, which grows at an annual rate of 2 % to 5 %, potentially outpacing traditional municipal solid waste growth [5]. Smartphones often have a shorter usage duration than their technical lifespan would allow [6]–[9]. Reasons for this include performance expectancy, compatibility, software obsolescence, price value, effort expectancy, and observability, which are crucial factors in adopting the latest versions of smartphones [10]. Extending smartphone service lifetimes can reduce the environmental footprint by decreasing device production through measures like improving repairability and recirculation by passing devices to additional users [11].

This study aims to explore how principles of sustainability can be established for electronics and software using the United Nations Sustainable Development Goals (SDGs) as a guide. The research focuses on free/libre open-source software's role in promoting sustainability through its application in electronics, programming, and internet development. This includes examining alternative mobile operating systems and decentralized online social networks, prioritizing user privacy and environmental responsibility. Finally, we mention legal aspects and frameworks that can further advancements within this domain at a later stage.

II. Open-Source Software

A. A Brief History of Free/Libre Open-Source Software

The history of open-source software is intricate and intertwined with that of free software. This distinction has evolved, shaped by various influential milestones in the field. Free/Libre Open-Source Software (FLOSS) is program code that enables users with the freedom to run, study, modify, and distribute it without restrictions or fees. It plays a vital role in addressing software-related obsolescence issues typically

associated with commercial closed source software [12]. The history of open-source software can be traced back to the computer science departments of US universities in the 1960s and 1970s, including Stanford, Berkeley, Carnegie Mellon, and MIT. During this period, programmers were encouraged to collaborate with one another, and some computer companies distributed software for free. However, by the 1980s, software had become proprietary, meaning it was owned by specific entities that prevented sharing and collective development of source codes [13], [14].

In response to this shift in software development, Richard Stallman, a former MIT software developer, initiated the free software movement alongside his colleagues. He announced the GNU (GNU's Not Unix) project in 1983, which aimed to create a complete free operating system software that was upward-compatible with Unix. The purpose of this initiative was to rekindle collaboration within the computing community and remove obstacles imposed by proprietary software owners. The GNU Project commenced in 1984, and in 1985, the Free Software Foundation (FSF) was established to recruit volunteers and raise funds for developing GNU [14].

The free software movement led to open-source software (OSS), which prioritizes practical considerations and business-related expectations in its licensing requirements. OSS goes beyond providing access to the source code by including criteria like redistribution, modified works, and technology neutrality. In contrast, free software focuses solely on the availability of the source code, without considering other factors. Both terms aim to promote collaboration and transparency in software development through an open-source model. There are numerous benefits and disadvantages associated with FOSS [13], [15]–[19], as summarized next. Benefits include:

1) Cost-effectiveness: FOSS offers no or low-cost alternatives to proprietary software, significantly reducing expenses for users and promoting financial sustainability.
2) Flexibility and customization: Users can modify and adapt FOSS to their specific needs, enabling personalized solutions and greater flexibility in software use.
3) Security and transparency: The open-source nature of FOSS allows for thorough scrutiny of the source code, enhancing security and providing transparency, which helps mitigate risks such as malware.
4) Collaboration and innovation: Open-source projects encourage collaboration among a diverse group of developers, accelerating innovation across various sectors.
5) Sustainability: FOSS promotes knowledge sharing, resource efficiency, and the longevity of hardware products, contributing to a more sustainable digital ecosystem by reducing electronic waste.

These benefits highlight how FOSS aligns with various SDGs, particularly SDG 9 (Industry, Innovation, and Infrastructure), but also contributing to other goals such as SDG 3 (Good Health and Well-being), SDG 6 (Clean Water and Sanitation), and SDG 12 (Responsible Consumption and Production).

A research paper about sustainable software products [49] introduced a model that connects observable attributes of software applications with their ecological footprint. The authors contend that although software is intangible, it can still exert indirect influences on natural resources through its requirements for hardware capabilities and user expectations concerning these demands. They propose criteria to evaluate the sustainability of software products from a lifecycle perspective, emphasizing energy efficiency, default settings, backward compatibility, and uninstallability. The study reveals substantial disparities between comparable software applications in terms of resource effectiveness or environmental impact. However, creating standardized labels for sustainable software solutions, expanding measurements to encompass more devices, integrating sustainability features into teaching and education, and incorporating these considerations directly into the development process when releasing new versions of software products are all relevant actions moving forward.

The academic sector has seen a significant uptake in the use of Free and Open-Source Software (FOSS), with GNU/Linux distributions—particularly those based on Debian—prevalent in university laboratories and offices due to their reliability and security. FOSS extends beyond operating systems, encompassing a wide range of applications that are integral to academic workflows. Python is widely used for its versatility in programming tasks, while desktop tools like Firefox, LibreOffice, and Zotero cater to web browsing, office productivity, and reference management, respectively. Moreover, messenger services such as Matrix and video conferencing systems including BigBlueButton facilitate collaboration among students and faculty. Audio and image processing tools such as VLC media player and ImageJ also provide valuable support in research and teaching. Learning platforms like Moodle also benefit from the collective development of FOSS communities, which often include university researchers. These tools are not only cost-effective, but also foster an environment of open innovation that aligns with academic values. [13], [20], [21] While FOSS offers numerous benefits, there are also potential drawbacks, such as:

1) Limited technical support: FOSS users might face challenges due to the lack of comprehensive technical support compared to proprietary software, potentially leading to slower resolution of issues and difficulties in problem navigation.
2) Compatibility challenges: Integration of FOSS with other systems or closed-source applications may not always be straightforward, resulting in compatibility issues that can affect productivity and system efficiency.
3) Security vulnerabilities: Although the open-source model generally improves security through community oversight, it also presents risks such as exploitation of outdated or unpatched code by malicious actors (e.g., widespread attack on numerous servers [25]).
4) Community maintenance burden: The sustainability of FOSS projects is contingent upon an engaged commu-

nity of developers for ongoing maintenance and updates. A decline in the developer community can jeopardize project continuity, potentially leading to abandonware or a lack of necessary support and updates.

These problems are mainly caused by the fact that FOSS developers mostly work on a voluntary basis and are not paid for their work [21]. Users thus do not have the role of customers who can insist that specifications for their product are adhered to. Compliance with specifications is left solely to the development team and their ethical standards for the use of their software. It is particularly problematic for the motivation of some projects if the FOSS developed unpaid and voluntarily by a committed community is adapted by large corporations and further developed into proprietary software. The development trajectory of the open-source Android smartphone operating system serves as an exemplar for this issue, highlighting how FOSS projects can be coopted by corporate interests in modern times. Initially launched under free and open-source principles, Google assumed control over the project, transforming it into proprietary software known as "Google Android" [22]. This shift has allowed the company to generate substantial profits from this platform. Scholars [24] argue that Google, as a dominant gatekeeper, continues to push the boundaries of law through its diverse business operations across multiple domains like search engines and software development projects such as Google Android [23]. There's an ongoing need for dialogue between legal experts, policymakers, tech companies including Google itself, users and consumer groups to strike a balance in promoting innovation and profit interest while ensuring fair competition practices and safeguarding individual rights within this rapidly changing digital landscape. Google's use of FOSS has also been scrutinized in relation to copyright issues surrounding several services (e.g., Google Android, YouTube, Google News). As a dominant player in the digital ecosystem with first-mover advantages across various sectors (e.g., search engines, online advertising (Google Ads)), questions have arisen if this power translates into a market abuse position. Google's engagement in legal battles over personal data protection, trademark law liability for Internet service providers (e.g., 'Viacom versus YouTube' litigation under Section 512(c) DMCA) highlight these concerns about balancing innovation with respecting intellectual property rights. Google Android brings up legal aspects of FOSS usage that require careful consideration within the context of private international law due to their global reach and potential impact on local jurisdictions' regulatory frameworks. [24]

It can be concluded that while there are challenges associated with open-source software, now it is evident that open-source software has significantly impacted various domains, including alternative open-source mobile operating systems (see [26], [27]) and decentralized online social networks.

B. Open-Source Software ?= Business

The operation and maintenance of complex infrastructures, such as social online networks and software for electronics like smartphones, also require a solid financial basis to be sustainable. This subject cannot be ignored within the overall context of the discourse [13].

A challenge faced by sustainable electronics projects is developing viable financial models that encourage cooperation without benefiting competitors. The public disclosure of open-source initiatives can enable market rivals to swiftly catch up, causing concern among proprietary software providers who prefer to keep their intellectual property concealed. This tension between closed and collaborative approaches remains a persistent issue in the software industry.

Proprietary software providers regularly attempt to safeguard their exclusive information by obscuring source code and imposing restrictive terms on usage licenses. Moreover, when research software transitions into commercial applications, the free (academic) version may become restricted, necessitating users to purchase a commercial license, which creates obstacles for adoption. This can hinder transparency and collaboration within open-source alternatives. Commercial software companies have expressed concerns about the potential risks posed by open-source software to their, licensing, business models and intellectual property rights [16], [28], [29]. One example is Microsoft, which stated in 2001 that the shift towards open-source is harming the industry. Over the years, it out that objections to the open-source model are unfounded. Thus, collaborative software development has faced resistance from specific sectors within the commercial software industry [30].

In the context of businesses, the presence of commercial open-source Software often leads to decreased prices for software products, negatively impacting profit margins for proprietary software producers [31]–[33]. However, consumer surplus and social welfare are likely to increase as a result in accordance with SDG 8 for decent work and economic growth. Commercial open-source offerings often raise concerns about reliability, security, long-term support uncertainty, total cost of ownership (TCO), and resources required for implementation and maintenance. Additionally, businesses may lack familiarity with FLOSS software or expertise in this domain.

Concerns about reliability/security issues along uncertainty surrounding TCO are major challenges faced by businesses considering commercial open-source offerings. However, others and we argue that potential drivers like cost savings from avoiding licensing fees; flexibility and customization options available through community and commercial support for development enhancements could encourage increased adoption rates among organizations. Individual aspects such as employees' resistance to change coupled with non-competitive leadership behavior may also negatively influence the adoption process [16], [28], [29], [34]. The adoption of FOSS in a commercial context has demonstrated its potential to enhance business success and efficiency, thereby promoting sustainability from an economic perspective.

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III. Alternative Mobile Operating Systems (AMOS)

Having extensively discussed hardware, open-source software - a crucial component required for device operation - and its significance in previous sections, our subsequent analysis will now shift the focus to specifically explore open-source alternative mobile operating systems (AMOS). This will be followed by an examination of decentralized online social networks (DOSNs).

Alternative mobile operating systems, so-called custom ROMs, are designed to minimize data distribution, to protect user privacy by withholding sensitive information and to extend the life-time of devices, which are no longer supported by the vendor [35], [36]. Preserving privacy and ensuring that user data remains securely stored on the device itself are the primary factors compelling users to opt for AMOS over default alternatives. Emphasizing privacy has an intriguing consequence; it concurrently limits the presence of personalized advertising on such devices. This aspect has long engaged researchers who explore various ways to address this issue, including employing efficient techniques like block methods to reduce overall energy consumption [37]–[39].

However, providing precise estimations for their usage is a complex task due to this very feature. In 2021, research indicated that cumulative around 3×10^7 users had installed LineageOS, presumably the most popular AMOS, on their devices [40]. In April 2024, approximately 2.56×10^6 active installations were recorded. Thus, only a small fraction are AMOS. The primary obstacle to installing AMOS is that vendors often secure the bootloader, which resembles a startup configuration like a computer's BIOS. To install AMOS, users must follow instructions to unlock the bootloader and ultimately flash their desired AMOS software onto the device. The vast number of these devices highlights the need for sustainable solutions in the electronics industry to address the environmental challenges posed by electronic waste and resource depletion.

For sustainable operation, efficient battery management is crucial within operating systems. Unfortunately, default mobile OSs often have limited and obscure settings for this purpose. Given that lithium batteries of smartphones' are the most delicate component, with a maximum guaranteed full recharge cycle count of 500 times, maintaining charge levels within optimal boundaries becomes essential to ensure longevity [42]. Fortunately, as battery management has emerged as a critical issue in open-source discussion forums, user-friendly and effective implementations have become the norm in most AMOS systems, addressing this concern effectively [36], [41].

Expanding transparency, collaboration, and resource efficiency into the realm of software development, open-source initiatives hold a crucial position [50]. Following, we investigate how alternative FOSS mobile operating systems (AMOS) and decentralized online social networks (DOSN) contribute to enhancing sustainable technology practices through innovative approaches [51].

IV. Social media

A. Gatekeepers for digital life

Social media has become an integral part of daily life due to the proliferation of smartphones and their accompanying applications. These include instant messaging platforms (e.g., WhatsApp), centralized online social networks (e.g., Twitter/X), e-commerce websites, and online payment systems. Smartphone apps have become integral to modern society's digital infrastructure, making them an essential part of daily life for many users [43], [44]. The use of social media continues to grow at an astonishing rate; in 2019, there were 2.95×10^9 active users worldwide, a figure that reached approximately 3.43×10^9 by 2023 [52].

Studies demonstrate that these networks can exert both positive and negative influences on environmental awareness, attitudes, and behaviors [45]. Factors such as content type, platform choice, active versus passive use all contribute to shaping green consumption habits. Environmental responsibility and perceived green value are among the factors that influence how different types of social network site usage can impact eco-friendly behaviors [46]–[48]. As more individuals turn to social media for communication, entertainment, and news consumption, it is crucial for stakeholders (e.g., researchers & policymakers) to understand the implications of this digital revolution [52].

We investigate here the usage of decentralized online social media on AMOS, considering the vast number of prospective users worldwide [52]. User selection bias shapes the usage patterns of different social media platforms. Age, gender, socioeconomic status, and location are some factors influencing his phenomenon. For example, Twitter/X has been found to have a male skewed user base in certain US areas while underrepresenting specific ethnic groups. Applications like Snapchat and Instagram target younger generations, whereas LinkedIn is more popular among higher-income users [53].

This phenomenon holds significance for our study given that we primarily engage with open-source technologies, thereby narrowing down our scope of analysis. Essentially, we will explore sustainability by focussing on open alternative mobile operating systems and decentralized online social networks. Users within these groups exhibit diverse motivations when it comes to utilizing open-source software and decentralized services. To put this into perspective, the overall user numbers are comparable to countries like Lithuania (ca. 2.5×10^6) or Belgium (ca. 11.8×10^6) in terms of population.

B. Decentralized online Social Networks

The emergence of decentralized social platforms such as the Fediverse enhances user privacy and contributes to a more sustainable digital ecosystem. This development occurs alongside initiatives like the IndieWeb, which is an inclusive community promoting personal web domains for sharing and connecting with others. By encouraging individuals to host their social data independently rather than relying on large centralized services, this approach fosters a more resilient and decentralized internet infrastructure [54].

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Decentralized Open Social Networks (DOSN) have seen significant development since 2009 with platforms like Safebook [55] and PeerSoN [56]. They federated by peer-to-peer (P2P) technologies to create a decentralized social network infrastructure. Safebook was a privacy-focused platform that stored user data locally, while PeerSoN used distributed hash tables for profile and content storage.

The Fediverse is gaining momentum as it provides users access to various independent online communities [54]. Adopting the W3C ActivityPub protocol (https://www.w3.org/TR/activitypub/) for server-to-server communication helped these networks gain more acceptance with Mastodon, a microblogging platform similar to Twitter/X since 2017 being a prominent service [57]. These application programming interfaces (API) enable developers to create applications that interact with these federated social networks and platforms, allowing for a unified experience across different services within the Fediverse. This network of interconnected decentralized social networks forms a distributed ecosystem, which enables users to interact across different federated servers, fostering an open and interoperable social media ecosystem with options like PeerTube (a video-sharing service similar to YouTube) or Pixelfed for image sharing (see Table. I).

TABLE I
THIS TABLE SHOWS A FEATURE COMPARISON OF SELECTED DECENTRALIZED ONLINE SOCIAL NETWORKS. MOST ARE PART OF THE FEDIVERSE, AN INTERCONNECTED NETWORK OF FEDERATED SERVERS RUNNING OPEN-SOURCE SOFTWARE LIKE MASTODON, PEERTUBE AND PIXELFED. *, NOT EXPLICITLY MENTIONED; §, OWN FEDERATION PROTOCOL BASED ON PEER-TO-PEER (P2P) TECHNOLOGY.

Feature	Mastodon	PeerTube	Pixelfed	Nostr
Microblogs	x			x
Photos	x		x	x
Videos	x	x	x	*
Hashtags	x	x	x	x
Mentions	x	x	x	x
Follow accounts	x	x	x	x
ActivityPub support	x	x	x	§

Launched in 2022, Nostr is a decentralized social network similar to microblogging services like Twitter/X but with unique infrastructure features such as relays. Relays act as open storage servers for user posts and ensure their authenticity through digital signatures using public keys. Thus, users securely send and receive posts across various relays without relying on single-server dependence or facing censorship issues. With 4×10^6 users and 60×10^6 posts in two years, a study examines the Nostr ecosystem's characteristics and challenges, focusing on relay availability and post replication strategies. Despite superior decentralization compared to Fediverse applications, it highlights financial sustainability concerns for free-to-use relays as a challenge [58].

The federated nature of the Fediverse aligns with several UN SDGs. The Fediverse promotes a more diverse and innovative ecosystem of social media platforms Table. I), fostering competition and technological progress (SDG 9). The open protocols and decentralized architecture of the Fediverse support the development of resilient and sustainable digital infrastructure. The Fediverse empowers users with more control over their data and online interactions [57], promoting digital rights and privacy (SDG16). The ability to moderate and block instances or users on the Fediverse can help address issues of online harassment and misinformation [69]–[71]. The federated and interoperable nature of the Fediverse encourages collaboration and partnerships between different social media platforms and communities (SDG17). This development towards decentralization aligns with the United Nations' SDGs [59], specifically Goal 16: "Peace, Justice, and Strong Institutions".

V. THE FEDIVERSE IN NUMBERS

To comprehend the current state of decentralized online socials networks (DOSN) we looked at the growth trends and the prevalence of various technologies and services within this ecosystem. The data was gathered for this study through two primary sources: aggregated scientific publications via OpenAlex and information from FediDB.org (see section VIII). The latter focuses on Fediverse development. While DOSN Nostr has garnered an impressive user base of approximately 4×10^6 since its launch in 2022 [58], our focus remains on the Fediverse due to its broader range of services, wider interoperability and greater coverage within the scientific community. In this quantitative study, we intend to gather data from these platforms to better understand the distribution of various technologies and services across them.

A. Development of the Fediverse between 2022 and 2024

The time series analysis of Fediverse developments between April 2022 and April 2024 revealed a strong positive correlation (rho = 0.94, S = 168.00, $p < 0.001$) between Fediverse user growth (FUG) and the number of servers (Fig. 1 A), as well as a negative correlation (rho = -0.66, S = 1128.00, p = 0.007) between FUG and monthly active users (MAU) (Fig. 1 B). Both correlations were statistically significant with p values less than 0.05, indicating that there is very strong evidence to support these relationships. The parameter monthly active user (MAU) refers to the total number of unique accounts who have engaged with the Fediverse within a given month. It is an important metric as it provides insight into the level of engagement, usage, and potential impact of the decentralized social media ecosystem on its users. However, it is essential to note that a decrease in MAU does not necessarily imply a decline in the Fediverse's overall impact or relevance. It could also suggest a shift towards more focused engagement within smaller communities, which may contribute positively to digital rights and privacy (SDG 16) by enabling users to have greater control over their data and interactions.

We have determined that the number of active users per month decreases while the number of servers increases. Therefore, we investigated how many monthly active users (MAU) are on average per server. Using the Welch Two Sample t-test, we examined the difference in the MAU/Server ratio between the first quarter of 2023 and the first quarter of 2024. In 2023,

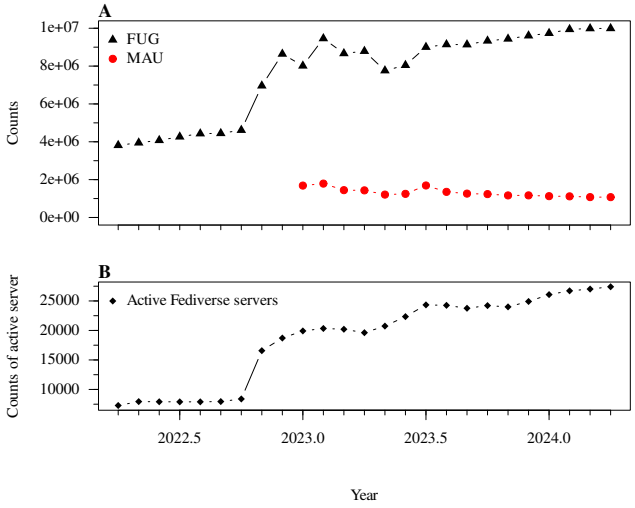

Fig. 1. Server statistics between April 2022 and April 2024. A) As user counts (FUG) ascend, so does the tally of operational servers, forming a correlation between both variables. B) The continuous growth of Fediverse servers reflects an ongoing expansion and adoption of this decentralized social media network. Notably, these increases are often accompanied by fluctuating trends, such as spikes in user registrations, which can contribute to the dynamic nature of the Fediverse ecosystem over time. MAU, monthly active users. FUG, Fediverse user growth.

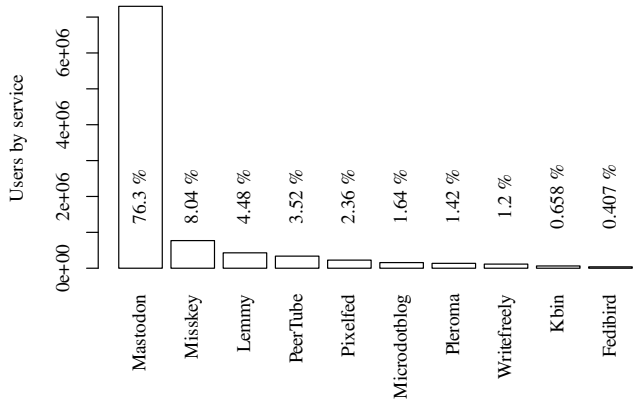

Fig. 2. User counts for various Fediverse services as of April 2024. Mastodon, with over 7.3×10^6 users, is the largest service in the Fediverse, followed by Misskey with 770×10^3 users, Lemmy with 429×10^3 users, and PeerTube with 337×10^3 users. The remaining services, including Pixelfed, Micro.blog (Microdotblog), Pleroma, Writefreely, Kbin, and Fedibird, have user counts ranging from 39×10^3 to 226×10^3.

there was an average of 79.29 $\pm$ 8.3 active users per server, whereas a lower number of 41 $\pm$ 1.8 MAU per server was observed in 2024. The effect is statistically significant, and large (difference = 38.29, 95 % CI [25.44, 51.13], t(3.29) = 9.03, p = 0.002; Cohen's d = 6.38, 95 % CI [1.61, 11.24]).

This analysis aligns with several UN SDGs. The positive correlation between FUG and server numbers indicates a growing interest in decentralized platforms for innovation (SDG 9) and sustainable infrastructure development, while the negative correlation between FUG and MAU could suggest efforts to maintain user privacy (SDG 16), reduce data concentration in large platforms, and promote partnerships among different social media instances (SDG 17). This development can also be interpreted as a positive signal in terms of SDG 3 "Good Health and Wellbeing". This is because studies are increasingly highlighting the health impairments associated with too much smartphone time [60].

B. Fediverse Services

Our analysis shows that Fediverse services can be broadly categorized into three main areas: Microblogging/Social Networking (Mastodon, Misskey, Micro.blog, Pleroma, and Fedibird), Content Sharing/Publishing (Pixelfed for photos and videos, PeerTube for video sharing, Writefreely for blogging) and Discussion/Forum platforms (Lemmy & Kbin).

As of April 2024, the distribution of user counts across Fediverse services is as follows: Mastodon leads with over 7×10^6 users. This significant presence among platform alternatives highlights its dominance in microblogging/social networking services, which have the highest number of users overall (Fig. 2). The remaining platforms exhibit varying levels of user counts within their respective niches: Misskey has 770×10^3 users and focuses on social networking; Lemmy has a substantial presence in community-driven content curation, with approximately 429×10^3 users. PeerTube, has around 337×10^3 users on its platform. Pixelfed is another notable service that caters specifically to image hosting and currently serves over 226×10^3 active accounts.

Micro.blog offers blogging capabilities for approximately 157×10^3 accounts who prefer this medium of expression, while more specialized services like Pleroma (with a user base of around 136×10^3) provide an alternative option within the microblogging/social networking category. Writefreely caters to those interested in blogging and has amassed approximately 115×10^3 users so far; Kbin serves about 63×10^3 accounts seeking discussion or forum platforms, while Fedibird supports around 39×10^3 accounts across its services (Fig. 2). This highlights the diverse range of offerings within the decentralized social network ecosystem known as Fediverse. The Chi-squared test for given probabilities/goodness of fit between service user counts, and a uniform distribution suggests that this effect is statistically significant, with $\chi^2 = 4.71 \times 10^7$ ($p < 0.001$) and an Effect Size Index value (Fei) of approximately 0.74, indicating strong evidence against the null hypothesis at a confidence level of 95 % [CI: 0.78-1].

This aligns with social networking being a fundamental use case for many internet users, and the decentralized, privacy-focused approach of the Fediverse appealing to those seeking alternatives to centralized platforms. Content sharing/publishing services and discussion/forum platforms have a significant user base, demonstrating that the Fediverse caters to diverse needs beyond just social networking. In summary, Microblogging/social networking services are currently most relevant and popular among Fediverse users, but the ecosystem as a whole serves various use cases and audiences [62].

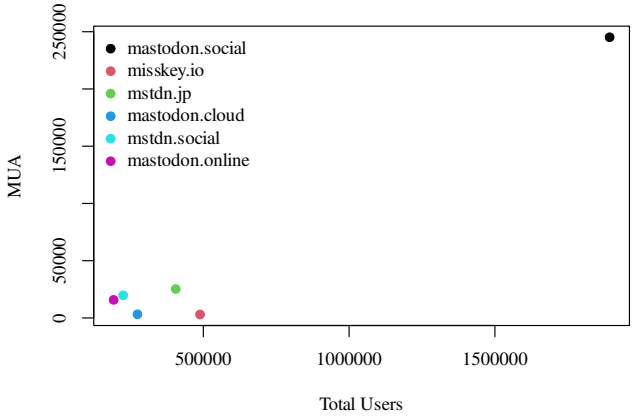

Fig. 3. Monthly Active Users across the top six Fediverse servers. The distribution of active users across six major Fediverse servers - mastodon.social, misskey.io, mstdn.jp, mastodon.cloud, mstdn.social and mastodon.online during April 2024 with a total combined user count amounting to approximately 3×10^6 accounts, where mastodon.social accounted for approximately 51 %.

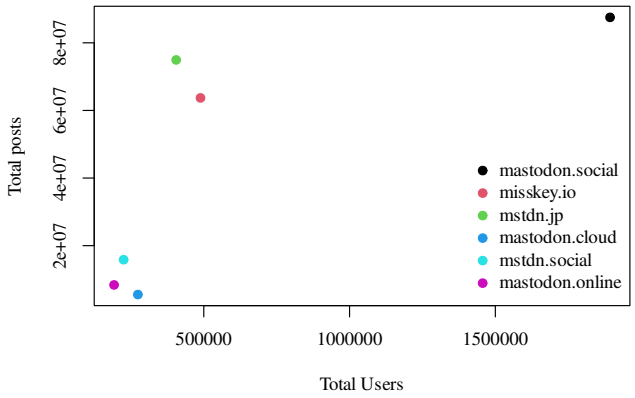

Fig. 4. Comparison between monthly active user (MAU) counts and total posts on popular instances. mastodon.social attracted more MAUs than misskey.io (50×10^6 posts) yet produced fewer total posts compared to mstdn.jp, which led in this category despite having an intermediate MAU count between the two other instances. Thus, servers with larger subscriber bases not always have engagement levels proportional to their user counts; indicating potential differences in user behavior and preferences across various platforms within decentralized social media ecosystems.

C. Fediverse servers - Tendency to centralize?

There is a weak but statistically insignificant relationship between the total number of users and MUA (rho = 0.26, S = 26.00, p = 0.658, Fig. 3). This suggests that while some connection may exist between these variables, it is not strong enough to reach statistical significance at a 0.05 level. Similarly, the Spearman's rank correlation coefficient (rho = 0.77, S = 8.00, p = 0.103, Fig. 4) reveals a strong positive relationship between the total number of users and the total number of posts on Fediverse servers; however, this result is also not statistically significant at a 0.05 level.

The total number of active users across all Fediverse platforms amounted to 9.572×10^6 accounts in April 2024. We analyzed the top six Fediverse servers (mastodon.social, misskey.io, mstdn.jp, mastodon.cloud, mstdn.social, & mastodon.online) to understand their user base and activity levels during this period. These servers had a total of approximately 3×10^6 users. That means, these six specific Fediverse servers are hosting around one-third of total active user counts. Thus, our analysis is leaving out other smaller-scale platforms that are part of this ecosystem. Among them, mastodon.social accounted for over half (51 %) while misskey.io had around a quarter-million subscribers, followed by mstdn.jp and Mastodon cloud each having nearly five hundred thousand users respectively; with the remaining two servers - mstdn.social and mastodon.online holding more than 10 % representation among all platforms combined.

D. Fediverse users - are you active?

The monthly active user (MAU) count ranged from Misskey's lowest of about 3×10^3 to the highest at nearly a quarter-million on mastodon.social. In terms of total posts, there were around 175×10^6 across all platforms with mstdn.jp leading in this category, followed by mastodon.social and then misskey.io (Fig. 4). This suggests that while some servers may have larger overall subscriber bases, their engagement levels might not necessarily be proportional to the number of users they attract or retain.

E. Geospatial distribution of the Fediverse

Fig. 5 reveals a significant uneven Fediverse server geospatial distribution. The majority of Fediverse servers are concentrated in a few countries, with the top 4 countries (United States, France, Germany, and Japan) accounting for over 2,400 servers, which surpasses 70 % of the total server count. While the top countries are predominantly Western, the data also shows a notable presence of Fediverse servers in Japan, which has the fourth-highest server count. This indicates an interest and adoption of the Fediverse in Asian regions.

This uneven distribution has implications for UN SDGs alignment, privacy protection, and geographical network dispersion. Encouraging further Fediverse development to global expansion can contribute toward a more inclusive and equitable digital environment with decentralized data storage spread over multiple nations, enhancing user security.

The dispersed server locations across various countries indicate a model that prioritizes privacy by not concentrating users' information in only several large platforms. The uneven distribution may also reflect differences in regulatory environments towards decentralized social media networks between different regions. A more balanced and equitable geospatial spread of Fediverse servers over time could promote digital inclusion, ensuring the benefits of these networks are accessible to a broader global population.

F. The Growth and Development of Scholarly Publications Related to the Fediverse: A Bibliometric Analysis

Despite a modest count of 81 articles, data from OpenAlex showcases a consistent rise in scholarly publications centered around the Fediverse over time, as illustrated by Fig. 6. From two publications in 2016, this number grew to 27 by 2023.

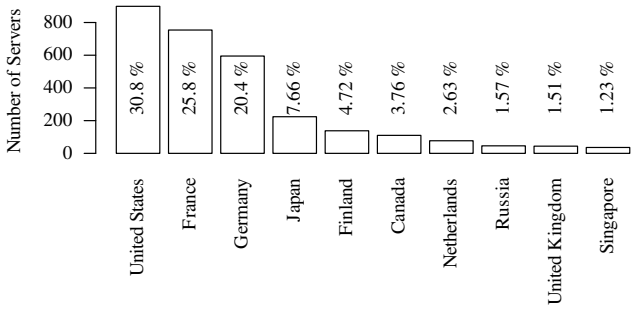

Fig. 5. Distribution of Fediverse server locations across countries in April 2024. The top four countries—United States, France, Germany, and Japan—account for over 70 % of the total server count, highlighting a concentration in specific regions. The χ^2 test suggests that the effect is statistically significant, and large (χ^2 = 3314.90, p < 0.001; Fei = 0.35, 95 % CI [0.34, 1.00]).

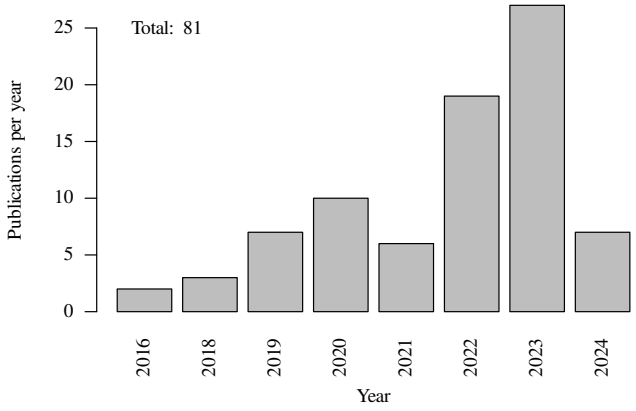

Fig. 6. Trend of publication activity related to the Fediverse from 2016 to 2024 (incomplete data for 2024, based on data from OpenAlex).

This trend suggests that the Fediverse has gained growing relevance and interest within the scholarly community. However, note that fluctuations observed are due to limitations of OpenAlex's data coverage and the inherent volatility and dynamism in research on the Fediverse. The 2024 data is incomplete as the year was not concluded; thus, the number of publications for this year likely increase, potentially altering the observed trend. English language papers dominate with other languages accounting for lower percentages (de: 12.3 %, en: 81.5 %, es: 1.23 %, et: 1.23 %, fr: 1.23 %, other: 2.47 %). Publications as articles were the majority; however, alternative publication forms also exist (article: 82.7 %, book: 3.7 %, book-chapter: 11.1 %, report: 2.47 %).

OpenAlex SDG classification (Fig. 7). Our analysis revealed that the majority (54.4 %) of works related to Fediverse primarily focused on SDGs 10 (Reduced inequalities) and 16 (Peace, justice, and strong institutions). No entries were found for Gender equality (SDG 5), Clean water and sanitation (SDG 6), Affordable and clean energy (SDG 7), Innovation and infrastructure (SDG 9), Responsible consumption and production (SDG 12) and Life below water (SDG 14).

Our analysis reveals that publications related to the Fediverse primarily focus on specific SDGs (Fig. 7). The Chi-squared test for given probabilities / goodness of fit of the SDG frequency to a uniform distribution suggests that the effect is statistically significant, and (χ^2 = 44.87, p < 0.001; Fei = 0.31, 95 % CI [0.20, 1.00]). The most addressed SDG is 16: Peace, Justice and Strong Institutions (28.3%), indicating authors' interest in how the Fediverse can promote peace, justice, and strong institutions as a decentralized social media ecosystem. This aligns with its emphasis on user privacy, data sovereignty, and content moderation capabilities.

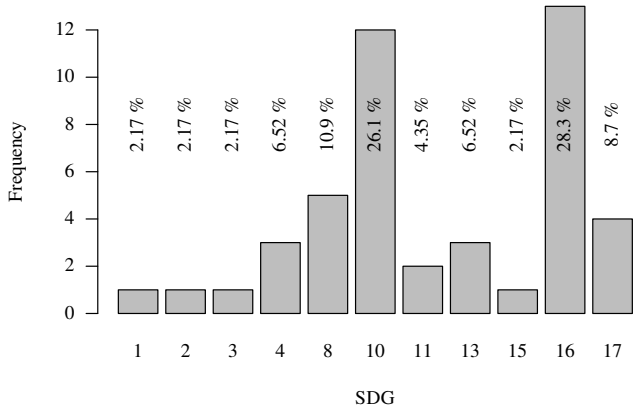

Fig. 7. Frequency of Sustainable Development Goals (SDGs) addressed in publications related to the Fediverse. 1: No poverty,2: Zero hunger,3: Good health and well-being, 4: Quality education (SDG 4), 8: Decent work and economic growth (SDG 8), 10: Industry, Reduced inequalities, 11: Sustainable cities and communities, 13: Climate action (SDG 13), 15: Life on land, 16: Peace, justice, and strong institutions, and 17: Partnerships for the goals.

The second most addressed SDG is 10: Reduced Inequalities (26.1 %), highlighting authors' interest in addressing digital access and power distribution issues. Authors also explored potential economic implications (10.9 %, SDG 8) of the Fediverse, such as new business models or job opportunities in a decentralized social media ecosystem. They may have considered how the Fediverse could improve access to and quality of education (SDG4), potentially through educational use cases on decentralized platforms.

Less frequent concerns included SDGs 1 (No Poverty), 2 (Zero Hunger), 3 (Good Health and Well-Being), 11 (Sustainable Cities and Communities), and 15 (Life on Land). This suggests that authors were primarily focused on social, institutional, and economic implications of the Fediverse. Additionally, there may have been some exploration into environmental impact or sustainability aspects (SDG 13) of the Fediverse, such as energy efficiency or carbon footprint of decentralized social media infrastructure. These observations align with findings by others [65], [67], [68].

There is a gradual increase in the number of publications related to the UN SDGs over time (Fig. 8). The distribution of SDG scores suggests that while most publications do not have a significant connection to SDGs, there is a notable number of publications that do, especially from 2020 onwards. While there are some publications with high SDG scores (above 0.4)

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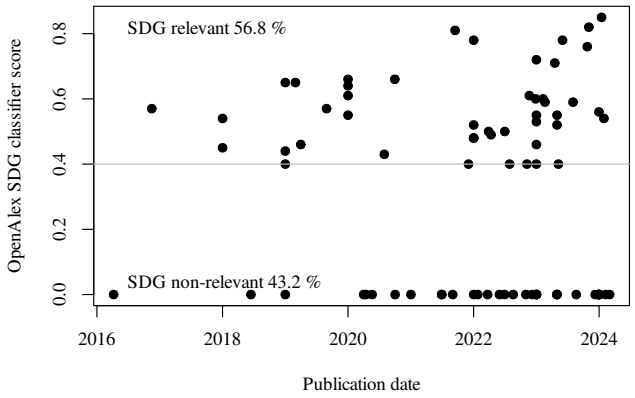

Fig. 8. Evolution of Publications OpenAlex SDG Scores Towards UN SDGs. An increasing trend in publications related to UN SDGs from 2016 to 2023. Most articles have low or no significant connection (OpenAlex SDG scores below 0.4). The number of high scoring works is growing since 2020, indicating increased focus on sustainability research. The highest SDG scores have been observed recently, suggesting stronger relevance to these objectives among academic communities.

throughout the period, the distribution of SDG scores appears to be uneven. In the earlier years (2016-2020), there are fewer publications with high SDG scores, with the majority having scores below 0.4, indicating little to no significant connection to the SDGs.

However, starting from 2021, there is a noticeable increase in the number of publications with higher SDG scores, suggesting a growing focus on SDG-related research and content. The highest SDG scores are observed in the more recent years, with several publications scoring above 0.7, indicating a strong connection to the SDGs. The highest SDG scores are observed in 2023, with several publications scoring above 0.8, indicating a strong relevance to the SDGs. This suggests that the academic and research community is increasingly interested in the UN's SDGs, likely in response to the growing global emphasis on sustainability and the 2030 Agenda. Overall, this indicates a positive development in the publication landscape, with a gradual shift towards more SDG-focused content over time. This aligns with the global efforts to accelerate progress towards the achievement of the SDGs by 2030.

VI. Discussion

Our study aimed to comprehensively evaluate how FOSS, DOSNs, and AMOS can serve as robust instruments for fostering a sustainable, resilient, inclusive, and adaptable digital ecosystem. This ecosystem is designed to not only tackle current challenges but also to meet future demands, ensuring that the benefits of these technologies are universally accessible to all stakeholders.

By accommodating various hardware and software configurations and offering long-term support, FOSS can mitigate smartphone obsolescence—a finding supported by research [11]. Since 2009, scholarly discussions about DOSNs have been ongoing, with many advocating for their utility in academic research and their potential to promote sustainable development in alignment with the SDGs [66]. These networks contribute to sustainability by embedding sustainable practices within their operations.

Our analysis reveals a statistically significant increase in the number of Fediverse servers, contrasting with relatively stable user numbers. This trend underscores the importance of understanding how these platforms balance growth and resource utilization to maintain their commitment to sustainability.

In our impact assessment, we evaluated the tangible effects of FOSS, DOSNs, and AMOS on internet sustainability. We use metrics such as user adoption rates, community growth to determine environmental benefits and risks measuring their influence. The time series analysis highlights the importance of monitoring both user growth and active usage in understanding the development trajectory of the Fediverse ecosystem. This information can be used to promote a more inclusive and equitable digital landscape that aligns with various UN SDGs. The Fediverse is expanding, raising critical sustainability questions. Our study reveals a paradox: while the number of Monthly Active Users (MAU) appears to be declining, the number of servers is increasing. This aligns with the philosophy (decentralization & federation) of DOSNs but prompts us to consider whether this trend can be reconciled with sustainable resource management—a question that warrants, e.g., further investigation into server production, maintenance, and operational environmental impacts. Comparing active AMOS & DOSN users with the population size of countries like Belgium highlights the significance of this digital ecosystem in a global context, often referenced in discussions about cryptocurrency's energy usage and its impact on climate change [76], [77].

To address these concerns, DSONs may need to prioritize sustainability by implementing measures. Encouraging more users to join each server, thereby distributing the load across a larger number of servers (SDG 9: Industry, Innovation, and Infrastructure) is one possible approach. This would reduce the environmental impact and energy consumption associated with running fewer but larger servers. Developing and employing energy-efficient technologies and data centers to reduce the overall environmental impact of DSONs (SDG 7: Affordable and Clean Energy & SDG 12: Responsible Consumption and Production). Promoting sustainable development practices throughout the entire network, including data center operations and server management. By prioritizing sustainability in these ways, DSONs can contribute effectively to achieving the SDGs while ensuring their long-term viability and minimizing their environmental impact. At the same time, it creates potential vulnerabilities in terms of data privacy and security.

SPAM, commonly associated with email, refers to unwanted, unsolicited messages that threaten the existence of the email system due to their massive and uncontrollable volume [63]. Interestingly, the Fediverse shares this vulnerability, as it is also a federated structure [69]–[71]. A large-scale analysis of federated platform policies, capabilities, and transparency mechanisms revealed significant challenges for robust and scalable governance [61]. Federated platforms face persistent threats such as coordinated behavior and SPAM.

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Key barriers include underdeveloped moderation technologies and insufficient financial models for trust and safety work. To address these collective safety and security risks, solutions were proposed by the authors, which include institutionalized shared responses to critical harms, built-in transparent governance into the system, investment in open-source tooling, and enabled data sharing across instances. Certainly, suggestion that can be applied for DOSNs.

Commercial central OSNs have extensive evidence of data analysis, processing and applications, particularly for personalized advertising purposes [64]. While, the goal of profit maximization is understandable, this approach comes with increasing costs from energy consumption (e.g., data processing (user profiling), storing data in storage systems and other processes. This also applies to emerging federated services like Threads (Meta) and Bluesky. Servers within the Fediverse have not systematically reported any analyses, processing, or applications of user data and usage data, particularly for personalized advertising purposes. Unlike central commercial OSNs, servers in the Fediverse often have cost covered by individuals (e.g., donations), resulting in no imminent comparable financial pressure or profit expectations. This factor positively contributes to sustainability.

Alternative mobile operating systems (AMOS) (e.g., LineageOS) and DOSNs (e.g., Mastodon) can have a significant impact on different entities (e.g., businesses (incl. small to medium-sized enterprises), academic institutions and NGOs). These impacts are diverse, ranging from improved data security and privacy to promoting digital inclusion and user sovereignty. They often prioritize data protection and user privacy compared to traditional operating systems and social networks. This can be particularly beneficial for entities concerned about the safety of their customers and employees. Utilizing AMOS can lead to cost savings as they typically consume fewer resources than proprietary systems. This can be especially attractive for small-to-medium enterprises with limited resources. AMOS and DSONs allow entities to tailor their digital platforms and communication channels according to their specific needs. This can result in increased customer satisfaction and a stronger brand identity. DOSNs promote digital inclusion by providing a platform for people. For entities committed to social justice, this can be advantageous.

European law [6] legislative activities aim to increase resource efficiency and combat obsolescence. For example, the Ecodesign Directive (Germany) provides legal frameworks for sustainable developments, while Voluntary Sustainability Standards (VSS), as discussed in [78], go beyond minimum requirements to reduce adverse environmental and social effects. These voluntary standards align with SDG 12 on responsible consumption and production [75]. Concrete ecodesign guidelines for electronic devices indirectly lead to increased sustainability through energy efficiency in product groups like lighting, IT equipment, repairability, recycling potentials, information disclosure about power consumption, materials composition and disposal procedures, with mandates on warranty periods, spare parts availability, take-back obligations creating incentives for a circular economy.

Software development is not subject to eco-design guidelines; however, the aforementioned trends and approaches contribute indirectly towards sustainability in this field. European legislation strives toward increased resource efficiency through legal frameworks like Germany's Ecodesign Directive. Software providers can voluntarily introduce eco-design guidelines into their products, with regular software updates and compatibility with older hardware extending both a product's lifespan as well its associated electronic devices', which may attract consumers. Repairability, modularity, recycling concepts are integrated into the development process to improve products' life cycles by making them easier to repair and recycle at end-of-life. Since AMOS, FLOSS, and DOSN can only be operated with electronics [6], we argue this will have an impact.

The Right to Repair (RTR) is a consumer rights movement that has grown steadily over the past decades, despite industry resistance [2], [72]. The RTR contributes to the United Nations' efforts to achieve SDGs, as right-to-repair laws reduce electronic waste and promote sustainable consumption [2]. As part of the so-called Green Deal, the RTR is being put forward at EU level [74]. In March 2023, the European Commission presented a proposal to promote the maintenance of goods, which amends the previous regulations for access to consumer repair access. An overview of the RTR history can be found in [2], [5], [79]. Environmental policies to promote RTR encourage manufacturers to implement appropriate product lifecycle management and reduce planned obsolescence. Manufacturers often use proprietary designs, so consumers & third-party services have limited access to faulty components. The RTR is a central aspect of digital rights that enables users to modify or repair their devices without relying on proprietary software or hardware. AMOS and DOSNs support this principle by offering open and modifiable platforms. This allows users to repair or improve their devices without being dependent on proprietary software or hardware.

This inadequacy not only affects repair, but also contributes to a throwaway culture, where entire devices are discarded because of a single faulty part or software. Many devices have embedded software that is closely linked to the hardware, making independent repair efforts difficult. This tight integration of hardware and software is a dual challenge. For owners, ubiquitous low repair thresholds, relative repair costs, limitations in repair infrastructure and technical ability to repair are important factors (lack of spare parts and maintenance manuals) that force a decision on consumers whether to repair or replace a device. Without access to source codes and tools, users are left in the hands of manufacturers, which impairs their ability to repair or improve devices or upgrades. [2], [73] To summarize, solutions that substantially support RTR are available, particularly in the case of AMOS and FLOSS.

VII. Conclusion

AMOS systems and DOSNs have considerable potential impacts on society and businesses. These include improved

data security and privacy through decentralization; cost efficiency due to reduced resource consumption; flexibility for customizing solutions according to specific business needs; promoting digital inclusion by providing access regardless of socio-economic status; supporting the right to repair via open platforms; contributing towards SDGs as set forth by United Nations. By empowering businesses with tools that enable them to establish themselves in the digital world and develop innovative business models promoting sustainable development, AMOS systems and DOSNs help create a secure online environment for all users. This study is relevant for academia and SMEs as it outlines a pathway to leveraging FOSS, DOSNs, and AMOS systems to achieve cost savings, enhance security, foster innovation, and contribute to global sustainability goals while navigating the complex landscape of business law.

Legal frameworks provide essential guidelines on licensing, intellectual property rights protection among others, while fostering innovation through shared resources, thereby creating conducive conditions towards sustainability goals. Further research could explore the impact of legal frameworks (e.g., General Public License (GPL)) on adoption rates; investigate how different licensing models (e.g., copyleft versus permissive licenses) affect development processes, or examine specific case studies where open-source software has been successfully implemented within businesses [21].

VIII. Methods

To provide an insight into Fediverse data, we utilized OpenAlex's [80] database and downloaded bibliometric data from their server via the query (https://openalex.org, query term 'decentralized online social networks') on March 29^{th}, 2024. Note, the coverage in OpenAlex is limited, as other databases are limited (see [81]). The Sustainable Development Goals (SDGs) are a global plan for promoting sustainable peace and prosperity while protecting our planet [59]. We used the OpenAlex SDG Classifier, an mBERT machine learning model [82], to assess works' relevance to these goals. We included the goals where the classifier predicts a score above 0.4. Data were processed using R (v. 4.3.1) with the RKWard IDE (v. 0.7.5z+0.7.6+devel3) [83] and relied on the data.table package (v. 1.15.2) [84] for importing, filtering, and preprocessing the data. Effect sizes for Spearman correlation analysis and Welch Two Sample t-test were labelled following Funder's recommendations, as described in [85].

IX. About the authors

Stefan Rödiger, a private lecturer at BTU Cottbus-Senftenberg, focuses on statistical bioinformatics, personalized medicine, and functional bioanalysis in his research. He has studied pharma-biotechnology, forensics and business law, been actively involved in the open-source community since 2002. (stefan.roediger@b-tu.de, corresponding author).

Martin Kögler received the Dr. Ing. degree in biotechnology from the Technical University Berlin, Germany in 2018. Since then, he has been working as the Senior Scientist at VTT Technical Research Centre of Finland in the field of sensing and integration. Apart from customer contract research, his focus areas and research interests are applied sensor technologies, embedded electronics and software integration as well as data interpretation.

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