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Research article

How user innovation communities contribute to sustainability transitions. An exploration of three online communities

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ABSTRACT

Online user communities have given rise to a new form of peer network collaboration. This paper examines three user innovation communities to assess their contribution to sustainability transitions, particularly in terms of exploring sustainable technical solutions and their integration into society. We study three user innovation communities by analysing internet forum interactions and conducting member interviews. To assess the impact of these communities, we use the technological innovation systems framework as an analytical perspective. Our analysis shows that user communities encompass a wide range of innovation activities and show great variation in their profiles: from strongly technology-oriented, rather anonymous networks to very broad-based communities that actively influence policy discourse, public acceptance and the social embeddedness of technologies. We conclude that innovation policy makers should recognise the transformative potential of this type of innovation and harness its potential to open up and explore alternative and more sustainable pathways.

1. Introduction

Private end users are essential actors in processes of innovation (Nielsen et al., 2016). This has been acknowledged in fields such as innovation, consumption or science and technology studies for a long time. Over the last 20 years the focus of this research has shifted from seeing users as passive consumers to seeing them as active players in sustainability transitions (Köhler et al., 2019). The field of transition studies has increasingly paid attention to and conceptualised the role of users or households. For example, Schot et al. (2016) have demonstrated that users play various important roles in developing and diffusing sustainable innovations, ranging from user-producers, user-legitimators, user-intermediaries, user-citizens to user-consumers. Despite such efforts, Raven et al. (2021) recently conducted a systematic review of the role of households in transitions and find that the literature has so far analysed it in a limited and fragmented way. They call for more research on household innovation across scales and socio-technical systems.

Despite a growing recognition of the importance of household sector activities for innovation in general (OECD, 2018; von Hippel, 2017) and for the development and diffusion of sustainable technologies in particular (Nielsen, 2020), decision makers still significantly underestimate the role of users as sources of innovation (Bradonjic et al., 2019). This misconception is all the more problematic as the internet has expanded the possibilities for users to share knowledge and create innovations collaboratively according to the model of "commons-based peer production" (Benkler, 2016). Coriat (2016) has introduced the term "commons-based innovation" to describe the recurring cycles of open input, self-organisation, and shared output that characterise these collaborative projects. Online

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forums, blogs, and discussion platforms make it easy for technology enthusiasts, tinkerers and hobbyists to exchange, pool and enrich knowledge even across large geographical distances without having to meet physically (Grabher and Ibert, 2014). In this way, loosely connected online user communities of like-minded people have emerged that create, manage and share collective knowledge resources or so-called digital (innovation) commons (Dulong de Rosnay and Stalder, 2020; Frischmann et al., 2014; Hess and Ostrom, 2007; Potts, 2019).

Collaborative user communities have also increasingly become a topic of the academic literature on open and user innovation. The focus has shifted greatly from a predominantly producer-centric perspective in the 1990s and early 2000s, which was mainly concerned with crowdsourcing and identifying lead users to harness user-developed ideas for the corporate benefit (Dahlander and Magnusson, 2008; Dahlander and Wallin, 2006; West and Lakhani, 2008). More recently, there has been a broader recognition of user innovators as actors in their own right, who can pool their expertise and resources to completely bypass producers in innovation development and diffusion (Baldwin and von Hippel, 2011; Gambardella et al., 2017; von Hippel, 2017). User communities self-organise collaboration to generate new ideas, solve problems, and create value. Their exchanges are sporadic, non-binding and usually based on reciprocity (Faraj et al., 2011; Faraj and Johnson, 2011). User innovators have been shown to invest a significant amount of time on innovation activities for a variety of motivations, such as for personal or family use, to help others and make the world a better place, for the pleasure of hacking and problem solving, or simply to learn or be part of a community (Chen et al., 2020; von Hippel and von Krogh, 2006; von Krogh et al., 2012). They often freely share their knowledge and open-source their designs so that they can be studied, modified, distributed, made and sold by anyone (Gächter et al., 2010; Harhoff et al., 2003; von Hippel and von Krogh, 2006, 2003).

Open-source developments have a considerable and growing economic impact. It is estimated that open source software alone contributes between €65 and €95 billion to EU GDP (Blind et al., 2021). However, open source collaboration now also extends to the physical fabrication and design of hardware (Bonvoisin et al., 2020; Gavras, 2019; Mies et al., 2020; Shah, 2005). It is expected to significantly influence technology fields, such as robotics and automation, machine learning and artificial intelligence, additive and distributed manufacturing.

Moreover, the new modes of collaborative innovation are met with great expectations for more sustainable production (Basmer et al., 2015; Bonvoisin, 2016; Helfrich et al., 2019; Kohtala, 2015; Kostakis et al., 2016; Parrino, 2022; Pearce, 2012; Petschow, 2016). A growing body of literature explores the relation of open-source and sustainability. Practice theory highlights the potential of open source communities as promoters of thrift, repair and reuse practices (e.g., Baier et al., 2016; Schmid, 2018; Smith, 2020). From a socio-technical transitions perspective, there is strong interest in engaging users in the development of a circular economy (Brown et al., 2021; Coppola et al., 2021; Panza et al., 2022; Prendeville et al., 2018), decentralised local manufacturing (Kohtala, 2015; Kohtala and Hyysalo, 2015; Kostakis et al., 2018; Petschow, 2016; Redlich and Moritz, 2016) and smart and renewable energy (Grosse, 2018; Hyysalo, 2021; Hyysalo et al., 2018, 2017, 2013).

We therefore argue that a transformative innovation policy aiming at sustainability transition (Haddad et al., 2022; Schot and Steinmueller, 2018; Steward, 2012) needs to better understand and harness this mode of collaborative knowledge development and diffusion in order to explore and stabilise alternative, more sustainable technological pathways unlikely to be pursued by regime incumbents with vested interests, sunk investments and their knowledge and capability path dependencies (Kohtala, 2017; Smith et al., 2016). Online user communities can help pluralise and 'open up' possible innovation trajectories. The use of distributed knowledge, the reconciliation of different goals and the exploration of alternative technological pathways give them an advantage over incumbents in the development of sustainable innovations (Kohtala, 2016; Osunyomi et al., 2016; Petschow and Peuckert, 2016). Indeed, the research agenda paper by Köhler et al., 4) argues that future sustainability transitions research should pay more attention to "new digitally mediated user collectives [which] take major intermediating roles amongst users in accelerating markets and technologies".

Our study is concerned with understanding how online user communities advance the development and diffusion of more sustainable technologies and practices and how they contribute to processes of sustainable innovation. We explore the phenomenon of collaborative user innovation through a case study approach in which we analyse three communities in terms of their activities and the mechanisms through which they influence sustainable innovation. The case studies are based on close examination of the peer networks formed by the interaction in online forums and interviews with community members. Their contributions to sustainable innovation processes are assessed using the functions of technological innovation systems (TIS) approach as an analytical perspective. We study the processes of coordination and information exchange within the communities and how their activities affect the formation and performance of the respective technological innovation system. The case studies examine and compare three established and internationally active user communities that use similar online forums: (1) *OpenStreetMap*, which develops open maps and geodata, (2) *OpenEnergyMonitor*, which develops electronics for monitoring energy consumption at home, and (3) *Precious Plastic*, which develops local ecosystems for recycling plastic. In this way, we make two important contributions. First, we re-conceptualise the TIS functions approach so that it can be used to analyse the role of user communities in developing and diffusing sustainable innovations. Second, we provide empirical insights on the mechanisms through which user communities influence sustainable innovation and socio-technical change.

The remainder of the paper is structured as follows. The next section presents the theoretical framework. This is followed by the presentation of our methodological approach. Section 4 presents the case study results. We will then discuss our main findings vis a vis existing literature and propose policy implications. Section 6 concludes.

2. Theoretical framework: a technological innovation systems functions approach for collaborative user innovation

As pointed out above, the focus of research on the role of users or households has shifted from seeing them as passive consumers to consider them as active innovators in their own right. Conceptually, the analysis builds on the functional approach to analyse technological innovation systems (TIS). This approach is used to study the formation of innovation systems around sustainable technologies in order to inform policy on drivers and barriers of sustainability transitions (Bergek, 2019; Bergek et al., 2015; Hekkert et al., 2007; Hekkert and Negro, 2009; Markard et al., 2015; Raven and Walrave, 2020). The TIS literature emphasises that different actors and institutions influence the development and diffusion of innovation and thereby is part of the family of analytical approaches (like national innovation systems, regional innovation systems, etc.) which are based on a systemic, networked and co-evolutionary understanding of innovation processes. This approach contrasts with earlier conceptualisations of innovation as a relatively linear process, starting with formal R&D in public labs or firms. Innovation systems theory instead emphasises the systemic nature of the innovation process, which is characterised by interactions and feedback loops across different actors and processes. The innovation system is intended to describe all socio-economic structures that influence the speed and direction of technological development. A TIS thus encompasses all actors, networks and institutions involved in the emergence, diffusion and use of a particular technology. However, it does not require conscious and purposeful action. Quite the opposite, it considers "all societal subsystems, actors, and institutions contributing in one way or the other, directly or indirectly, intentionally or not, to the emergence or production of innovation" (Hekkert et al., 2007). This agnostic stance and the systemic approach makes the approach well suited to studying collaborative user innovation.

In addition to analysing the structural components of a TIS, the TIS functions approach puts an analytical emphasis on the functional requirements that the system must fulfil to develop successfully, such as knowledge development and diffusion, entrepreneurial experimentation or market formation. It defines core functions that need to be provided for the system to perform, i.e. for the technology in question to be developed and diffused (Bergek et al., 2008; Hekkert et al., 2007). This analytical framework allows to identify and describe the contributions of system components to the overall performance of the system and to track their development over time, to identify strengths and weaknesses, etc. In this study, we use it to investigate how online user communities contribute to innovation for sustainability. The communities are understood as specific actor networks that potentially influence the way TIS functions are fulfilled.

The case studies illustrate how innovation takes place in online user communities and through which activities they affect TIS functions and thereby contribute to the development and diffusion of technologies. In line with the widely used definition of the Oslo Manual, the OECD guide to measuring innovation, we understand technology as "a set of instruments, methods, procedures or systems used by people to improve their environment, to solve problems and to achieve goals" (OECD, 2018). The definition emphasizes the purpose of technology as a tool rather than simply the application of scientific or technical knowledge and it highlights the role of human agency in its development and use.

To understand how user communities collaborate, we study their online interactions. Online forums offer users the opportunity to interact with like-minded people and to seek help with questions or technical problems for which there are few other sources of information. All the forums considered here have a similar basic structure. After registering, anyone can author a post in the forum, which can be read and answered by other registered users. The forums are subdivided into thematic sub-forums to which the contributors assign their posts. All related posts in a sub-forum are called threads. Each post that does not reply to another post starts a new thread. Through the mutual reference of posts, online forums map the interaction between community members over time and can thus provide insights into the relationships between different parts of the community (see Fig. 1).

The conceptualisation of TIS functions makes it possible to 'diagnose' the performance of a particular TIS. Functions refer to a set of

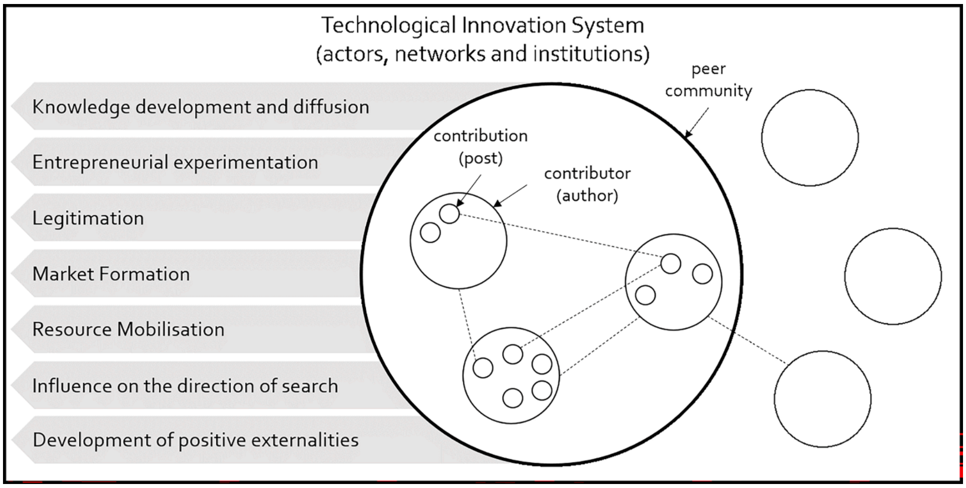

Fig. 1. An online user community as network of actors within a TIS.

processes that an innovation system around a particular technology needs to perform in order to successfully develop and diffuse the technology. Functional analysis enables a comparison of very differently structured innovation systems and to assess the contribution of different structural elements, including online user communities. By identifying key processes that are essential for system performance, the TIS functions approach is principally conceptually open to include contributions from non-firm actors and their informal networks, even if these actors do not intentionally aim to perform these functions. The framework is therefore well suited to integrating collaborative innovation activities of user communities into the study of technological developments, if the functions are refined to also reflect the different motives, the particular logics of action, coordination patterns and dynamics of these actors.

Drawing on Bergek (2019), we distinguish seven functions: (1) knowledge development and diffusion (KDD), (2) entrepreneurial experimentation (EE), (3) influence on the direction of search (IDS), (4) market formation (MF), (5) legitimation (LEG), (6) resource mobilization (RM) and (7) development of positive externalities (PE). Although the TIS approach was developed with markets in mind, the functions are sufficiently abstract to be (at least partially) applicable to innovation processes in user communities. Our re-conceptualisation of the TIS functions approach in *Table 1* draws on the aspects of the functional descriptions that are relevant to the context of collaborative user innovation.

We believe such a use of the TIS approach is legitimate and analytically useful. We contend that this broader interpretation of innovation processes, where innovation is not necessarily performed by economic agents for profit motives, is timely since the updated OECD Oslo manual 2018 now explicitly includes all actors (using 'units' instead of 'firms') and acknowledges the diffusion of innovations also outside of markets (referring to 'has been made available'). We therefore argue that our approach, although developed specifically with collaborative user communities in mind, is more broadly applicable to other non-firm actors. In the following, we summarise relevant literature from the fields of open and user innovation and sustainability transition studies to conceptualise the contributions of user communities to the individual functions of a TIS.

Even though their contributions to knowledge development and diffusion (KDD) are likely to be more unsystematic and serendipitous compared to conventional R&D,[1] online user communities may significantly foster knowledge development and diffusion by bringing together people with different backgrounds and expertise to share information and experience on a topic of common interest (Benkler, 2006; Hienerth et al., 2014; Hyysalo, 2021; Lee and Cole, 2003; von Hippel, 2017, 2005). Relevant information about a new technology is pooled, recombined, and diffused amongst community members via internet forums. Forum users learn from one another through discussion, feedback, and shared experiences, leading to the co-creation and diffusion of new ideas (Franke and Shah, 2003; Harhoff et al., 2003). Through processes of social learning, these individuals gain a deeper technological understanding, including the challenges and opportunities involved in developing and implementing new technologies (Hyysalo et al., 2018). In this way, user communities enable members to combine and leverage efforts, and help the diffusion of resulting innovations (von Hippel and Paradiso, 2008).

Online user communities do not systematically conduct entrepreneurial experiments (EE), but they still contribute to the underlying objective of the EE function, which is the reduction of technological uncertainty that holds market actors back (Allen and Potts, 2016). By collecting and sharing multiple experiences of community members in dealing with the new technology, feedback about the feasibility and potentialities of the technology and important "information regarding the value proposition or existence of a potential entrepreneurial opportunity" (Agarwal-Tronetti and Shah, 2014), the community accumulates relevant 'information about the innovation' (Potts, 2019). As a result, community members may also develop entrepreneurial ambitions and begin to commercialise community-based innovations (Cuntz and Peuckert, 2023; Halbinger, 2018).

The influence on the direction of search (IDS) function is essentially about coordinating innovation efforts in the technology sector to bundle resources and strengthen novel development pathways. In addition to mechanisms for internal coordination, such as standard toolkits, roadmaps, shared knowledge repositories, online surveys and polls, task assignments, etc., online user communities may also influence the search for solutions of other actors in the field. Because these communities bring together first-hand information about latent user preferences for design and functionality, as well as individual user experiences, they are expected to foreshadow emerging markets (Thomke and von Hippel, 2002) and perhaps even exert collaborative pull effects (Hienerth and Lettl, 2011). External actors therefore may seek to identify lead users (Belz and Baumbach, 2010; Hienerth and Lettl, 2017; Kratzer et al., 2016), to take up promising ideas (Hoornaert et al., 2017; Resch and Kock, 2021) and to be responsive to new technological developments within the community.

By making their designs freely available to potential users, online communities can have considerable impact on the formation of new markets (MF). Start-ups or established firms may take up innovations to exploit them commercially. But even if these innovations are not commercialised, the ability of users to self-provision will shape market demands. In this context, Gambardella et al. (2017) distinguish between 'user-contested markets' where self-provisioning can substitute for products offered on the market, and 'user-complemented markets' where it increases demand for complementary goods offered on the market. Under certain circumstances, it can be advantageous for producers to support rather than compete with user communities.

As far as the legitimation function (LEG) is concerned, the activities of user communities can have a significant legitimising effect, even if their members do not intentionally pursue this goal. Technology-oriented movements tend not to be directly involved in proactive legitimacy-creating activities, such as building advocacy coalitions and lobbying (Hess, 2005). However, the community can influence social acceptance by adapting the technology to the existing socio-technical system or discursively challenging opposing institutions (Smith and Raven, 2012). Hyysalo (2021) for example points out that the ideology-free 'appreciative-critical' discourse

[1] There is also an important discussion about the role of serendipity in formal R&D processes (see e.g. Yaqub, 2018), so the differences are gradual rather than of a categorical nature.

Table 1
Innovation System Functions in the context of collaborative user innovation.

TIS Functions	Original definition by Bergek, 2019	*Re*-conceptualisation in the context of collaborative user innovation
(1) Knowledge development and diffusion (KDD)	"are processes that result in a broadening and deepening of the knowledge base of a TIS, sharing of knowledge between actors within the system and new combinations of knowledge as a result of this" (p. 204).	How the depth and breadth of the relevant knowledge base changes through (peer) learning and how the knowledge diffuses and recombines through (user) interaction and the (online) exchange of information.
(2) Entrepreneurial Experimentation (EE)	"Entrepreneurial experimentation refers to such processes of uncertainty reduction through trial-and-error experimentation with new technologies, applications and strategies." (p. 205).	How uncertainty regarding the new technology is reduced through trial and error and the practical application. This function can also be performed by actors other than business entrepreneurs, including users and intermediaries in online communities.
(3) Influence on the direction of search (IDS)	"Influence (or guidance) of search processes refers to mechanisms that influence in what direction firms and other actors look for new opportunities and to what problems and solutions they apply their resources" (p. 207).	How the (online) user community influences the search direction in knowledge development and the choice between different technological options, for instance, by revealing latent user preferences or by coordinating on de facto standards.
(4) Market formation (MF)	"Market formation refers to the opening-up of a space or an arena in which goods and services can be exchanged in semi-structured ways between suppliers and buyers and includes sub-processes such as articulation of demand and preferences, product positioning (including pricing and segmentation), standard-setting and development of rules of exchange" (p. 206).	How (social) demand for the new technology is articulated and actually met by online communities enabling users to self-provision, affecting commercial prospects and the emergence of new markets.
(5) Legitimation (LEG)	"Legitimation refers to the process of the new technology, its proponents and the TIS as such achieving regulative, normative and cognitive legitimacy in the eyes of relevant stakeholders, that is, increasingly being perceived as complying with rules and regulations (legal behaviour), societal norms and values (morally acceptable behaviour) and cognitive frames (expected behaviour)" (p. 2010).	How social acceptance of the new technology and its conformity with institutions is achieved by shaping social discourse and transforming the technology into objects that complement existing socio-technical systems.
(6) Resource mobilization (RM)	"Resource mobilization refers to the system's acquisition of different types of resources that are needed for innovation to occur, most notably financial resources (capital), human resources (competence and labour) and complementary assets (for example, infrastructure)" (p. 209).	How (online) user communities mobilise human labour and skills, financial resources and complementary infrastructures, for example, through the investment of time and effort, donations or the provision of digital services.
(7) Development of positive externalities (PE)	"Development of positive externalities refers to the creation of system-level utilities (or resources), such as pooled labour markets, complementary technologies and specialized suppliers, which are available also to system actors that did not contribute to building them up" (p. 211).	How free benefits and utilities are developed within the system, for example by providing technological knowledge and technical support, but also specific information about the technology not available from market actors.

prevalent in technology-oriented community forums proves very effective in increasing the legitimacy of the focal technology in society.

In terms of resource mobilization (RM), user communities can draw on a wide range of participation incentives to attract (human) resources for technological development. Individual benefits of community contributors are related to reputation building (Lerner and Tirole, 2003, 2001), participation-related self-rewards (von Hippel, 2017), and altruistic and idealistic motives, such as the desire to help others or contribute to social change (Chen et al., 2020; von Krogh et al., 2012). Most importantly, by pooling valuable information about the technology and its applications, user communities create and share an innovation resource that aspiring entrepreneurs can draw on (Allen and Potts, 2016; Potts, 2019; Shah and Mody, 2014).

Regarding the development of positive externalities (PE), user communities can create considerable knowledge spillovers by freely sharing their designs and experiences (e.g., Franke and Shah, 2003; Harhoff et al., 2003) amongst a variety of participants that are geographically dispersed (Grabher and Ibert, 2014) and range from highly skilled technical experts over influential peripheral contributors to passive observers that may learn and diffuse the ideas (Meelen et al., 2019). As user-side intermediaries, they provide peer support (e.g., Hyysalo et al., 2013) and specific information about how the technology works that is not otherwise available. This enables users to develop competences, articulate demand and adapt the technology to the needs of different contexts (Hyysalo et al., 2018). In this way, important barriers to upscaling and broader knowledge dissemination may be removed and the reach of the focal technology is extended beyond niche actors, tech enthusiasts and early adopters to mainstream users (Hyysalo, 2021).

3. Methodology

Since collaborative innovation in online user communities is a relatively new phenomenon, a case study approach is considered appropriate to develop a deep and situated understanding of how such communities 'work' and in what ways they can be seen to contribute to the fulfilment of TIS functions. To identify suitable communities involved in the collaborative development and the open diffusion of sustainable technologies and using online forums for knowledge exchange, we first screened well-known project hosting platforms such as *Wikifactory, Fablab.io* and *Instructables* for potential cases and conducted informal interviews with makerspace users.

It turned out that of the large number of interesting projects, only a relatively small share had an active online user community that regularly exchanged ideas over a longer period.

The final selection of the cases (see Table 2) was based on the following criteria:

- **Online forum interaction**: The selected communities use similar online forums whose contributions can be traced for at least the investigated period from 2017 to 2019.
- **Community size**: The selected communities have a large number of forum contributors, ranging between 2000 and 6500 for the investigated period.
- **Activity level**: The selected communities have been very active over the investigated period, with roughly 20,000 to 150,000 forum posts.
- **Technology domain and sustainability field**: Communities were selected to cover both software and hardware domains with relevance to different sustainability fields.

We conceptualise the selected communities as networks of actors that contribute to the development and diffusion of specific technologies. The role of each community is analysed by tracing their contribution to the fulfilment of the TIS functions. To do this, it is necessary in each case to define the system boundaries of the respective TIS. Specifically, OEM was assessed for their contribution to ‘smart energy monitoring technologies’, OSM for their contribution to ‘geo-information services’ and PP for their contribution to ‘local plastics recycling’.

The case studies are based on a mixed-methods approach that included 18 semi-structured interviews with members of the communities (see Table 3) and a quantitative network and contribution analysis based on the data available from the online forums. In this way, possible connections between the structure and performance of the networks were investigated.

The forum data was analysed regarding content categories (technical, organisational and other issues) as well as key figures of contribution behaviour (e.g., number of posts per user, length of contributions, response rate). For better comparability, we limited our analyses to forum posts that were created in the period from 01/2017 to 12/2019. In total, the resulting dataset contained more than 200,000 posts (20,000 threads) from 12,000 registered forum users. Following approaches of social networks analysis in software development (Herbold et al., 2021; Toral et al., 2010), we modelled simple interaction networks for each community, assuming that knowledge was exchanged between forum users who contributed to the same discussion threads. These interaction networks were represented by an undirected graph, in which nodes represent contributors to the online forum, and the weighted edges represent their interactions. We will refer to the following measures to describe the structure of the analysed networks (Boccaletti et al., 2006):

- **Network density** measures the proportion of existing connections on all possible edges (in a network with full density, all contributors would be connected). It is related to the intensity and comprehensiveness of interaction between members of the community.
- **Casual contributors** (the proportion of users with no more than one contribution) is a measure of inexperienced and experimental interaction in the community.
- **Core contributors** (the proportion of users in the largest subgroup in which all interact) is a measure of the concentration of power in the community.

The interviews aimed to elicit key activities and processes in the communities relevant to the fulfilment of TIS functions. The interviews were semi-structured, lasted about half an hour to an hour, were recorded and transcribed. The interview questionnaire was designed to obtain personal assessments of TIS-relevant processes in the network. The interviewer could choose from a set of diagnostic questions, to steer the conversation towards potentially relevant activities of the community. Assuming that the interviewees were not familiar with the theoretical framework, they were asked about their experiences and expectations regarding community collaboration without reference to specific TIS functions. Amongst other things, interviewees were asked how technical knowledge was developed and passed on in the networks, how people worked together and exchanged information, how people joined and what common goals they perceived, how decisions were made and what resources were used.

Table 2
Selected communities.

	OpenStreetMap (OSM)	OpenEnergyMonitor (OEM)	Precious Plastic (PP)
Foundation	2004, London	2009, Eryri (Snowdonia)	2012, Eindhoven
Technology	open maps and geodata	open-source technologies for monitoring energy consumption at home	ecosystems for local recycling and creative reuse of plastic waste
Forum URL	https://forum.openstreetmap.org	https://community.openenergymonitor.org	https://davehakkens.nl/community/forums
#contributors (investigated)	21.954 (6.494)	3.189 (2.052)	4.688 (3.484)
#posts (investigated)	806.208 (146.612)	64.941 (37.040)	36.906 (18.588)
Domain	data processing (mainly software)	Electronics (hardware and software)	material processing (hardware)
Field of sustainability	green mobility	smart energy	circular economy

Table 3
List of interviews.

ID	Community	Country	Date	Duration (min)
#1	OEM	UK	2021–03–16	38
#2	PP	NL	2021–02–17	45
#3	PP	DE	2021–01–27	66
#4	PP	DE	2021–01–26	50
#5	OEM	UK	2021–03–17	45
#6	OEM	CA	2021–02–18	26
#7	PP	NL	2021–02–10	36
#8	PP	NL	2021–02–01	52
#9	PP	NL	2021–02–11	48
#10	PP	DE	2021–02–24	49
#11	PP	CN	2021–03–18	33
#12	OSM	DE	2021–07–01	39
#13	OSM	IT	2021–07–27	66
#14	OEM	BR	2021–07–07	48
#15	OSM	PL	2021–07–25	54
#16	PP	DE	2021–08–16	48
#17	OEM	ES	2021–08–20	30
#18	OSM	DE	2021–08–17	44

Recruitment of interviewees was supposed to follow a snowballing approach. First, we identified and contacted active members by analysing posts in the community forum. In the interviews, we asked them to suggest further interviewees. As this approach only worked out for the PP community, we identified active members of the other two communities based on their contributions in the online forums and/or badges (awards, or thematic markings of the user profiles in the forums) and contacted them with private messages.

The transcripts of the interviews were analysed independently by two researchers using MAXQDA qualitative analysis software. The TIS functions (as in *Table 1*) served as a deductive coding system. Activities and community interactions mentioned by the interviewees were coded according to which system functions they help to fulfil. Intercoder reliability was ensured by iteratively defining coding rules according to Kuckartz and Rädiker (2019). In the synopsis of the codes, an assessment was made about the importance of the community's contribution for each TIS function.

4. Case studies of three user innovation communities: openstreetmap, openenergymonitor and precious plastic

In this section we present the results of the case study analysis. First, we briefly describe the history, founders, main goals and supporters of each community, as well as their relevance for innovation and sustainability transitions. We also discuss key differences between the communities, particularly in terms of their network structures, composition, coordination and collaboration patterns. After this preliminary assessment, we use the interview evidence to ascertain the contributions of each community to innovation processes through the TIS functions.

4.1. OpenStreetMap

The purpose of OSM is to develop a world map that can be freely used by everyone. OSM contributors are committed to the ideas of open source, transparency and free information. The community collects, processes and publishes geospatial information. Even though also data from aerial photographs and GPS tracks are included in the database, important information about rivers, railways, roads, houses, forests and much more is compiled by the huge community of mappers that is organised in local subgroups all over the world. OSM can be described as a 'crowdsourcing' community, as it is about collecting information from many contributors, even if in fact only a small percentage of the more than 8 million registered users make significant entries into the database.

The OSM project was initiated by Steve Coast, a computer science student at the University College London in 2004. Two years later, the OSM Foundation was established to organise the community and provide the digital infrastructure. The technical development of the software tools for the collection and processing of crowdsourced geo-data is coordinated by the so-called Engineering Working Group at the OSM Foundation.

The OSM database is now used by all kinds of actors and the community has also spawned business start-ups. One well-known example is *Mapbox*, a commercial provider of customised online maps based in California, which has raised significant amounts of venture capital funding and now employs more than 650 people. OSM data is used in scientific research, for instance to analyse parking spaces in the city of Berlin, and in commercial products, for example for navigation devices. Public institutions and enterprises, like the Polish toll system, and large multinational companies, like Amazon, Facebook or Tesla, use the map and even pay developers to further improve it. An important area of application is disaster management and humanitarian aid, which mobilises many volunteer contributors. Free and open access also enables actors with niche needs and non-profit initiatives to use and contribute to geospatial data, including actors in the sustainability fields of ecotourism, environmental monitoring, shared mobility services and public transport.

4.2. Open energy monitor

OEM develops and provides open-source electronic hardware and software for monitoring energy consumption at home. It enables users to metre, analyse and regulate energy use and to monitor energy-relevant parameters such as temperature and humidity from a smartphone, tablet or computer. The two Welsh OEM founders Trystan Lea and Glyn Hudson began experimenting with Arduino modules and plug-in boards in 2009 and documented their progress online. The OEM internet forum has become a vibrant platform for sharing experiences, ideas and designs for cost-effective and adaptable solutions.

OEM is a typical ‘tech community’, its contributors being tech-enthusiasts primarily interested in DIY solutions for their personal use. Participation in the online forum requires considerable prior technical knowledge, which makes it rather difficult and unattractive for inexperienced users to join. As a result, the peer group remains relatively closed and homogeneous, its members are mostly technically trained and often have a background in electronics or computer science.

Although individual members do pursue sustainability goals, this is not a shared view in the community. In fact, the environmental benefit is only a marginal topic in online discussions. Cost savings and manufacturer independence are frequent motivations for engaging. Nevertheless, by raising awareness of home energy consumption and helping to identify and leverage potential savings, the community is highly relevant to sustainability. End consumers are enabled to participate in the energy transition by reducing their personal consumption – an activity much less explored in the sustainability transitions literature than prosumer engagement in energy production, for example through community renewable energy schemes.

4.3. Precious plastic

PP aims to recover raw materials from plastic waste and process them into simple plastic products by developing low-cost and easily replicable machines. The idea was developed in 2012 by Dutch design student and artist activist Dave Hakkens as part of his final project at the Eindhoven Design Academy. It addresses the global plastic waste problem by advocating for local recycling solutions. Reusing the resulting plastic waste locally is intended to create awareness, shorten transport routes and enable local value creation. For this purpose, the PP development team has designed a complete ecosystem, ranging from the collection, shredding and processing of plastics to the sale of the recycled products. An international community of activists is putting the basic idea of PP into practice. In doing this, they can draw on collected information about the material properties of plastic, blueprints for small open-source recycling machines, practical instructions and workshops on plastic processing, shared product designs for recycled plastic objects and business models. The project website features appealing pictures and videos that showcase the international activities and an online forum that is used to exchange ideas and experiences with practical implementation.

The PP community can perhaps be described as a ‘grassroots innovation’ (Seyfang and Smith, 2007) initiative, as it pursues the political goal of combating plastic waste with the development of alternative recycling ecosystems. Members often want to make a personal contribution to improving the world and enabling sustainable lifestyles by creating awareness for environmental degradation and finite resources. These common values and goals form the basis for a strong identification of members with the community.

4.4. Distinguishing features of the communities

Despite obvious similarities, the communities studied also show considerable differences on closer examination. Analysing the online forum data reveals differences not only in the content, but also in the structure and composition of the contributor networks formed. Using simple network metrics, this section identifies and compares key differentiators between the communities studied, considering predominant motivations and basic orientations, as well as prevailing communication and collaboration patterns (see Table 4).

It is important to note that online forums may only cover part of community interactions. This is certainly true for the OSM and PP community, whose members stress the importance of offline meetings for community building, knowledge sharing and coordination. For example in the interviews, PP members report considerable difficulties in solving technical problems via the online forum and

Table 4
Comparison of cases.

	OSM	OEM	PP
Communication	online and offline	predominantly online	online and offline
Community type	‘crowdsourcing’	‘tech community’	‘grassroots innovation’
Forum content structure technical / organisational / other issues	8.1 % / 0.8 % / 91.1 %	85.1 % / 14.9 % / -	71.4 % / 27.9 % / 0.7 %
Diversity and openness	high	low	high
Casual contributors Proportion of users with max. one contribution	37,4 %	23,1 %	55,5 %
Coordination	decentralised (local)	decentralised	centralised
Core contributors Largest subgroup in which all contributors interact	3,3 %	5,3 %	9,4 %
Collaboration patterns	hybrid	crowd	community
Network density Proportion of interacting member pairs (of all possible pairs)	0,9 %	0,9 %	1,7 %

Table 5
Assessment of community activities' contribution to TIS functions.

OSM	OEM	PP
Knowledge development and diffusion (KDD)		
iterative improvement and broadening of the knowledge base The community develops and improves software tools for mass collection and processing of geospatial data. New tools are shared with the community and adopted if they prove to be useful. However, knowledge exchange is hampered by the high proportion of occasional contributors (especially mappers).	*deepening of the technical knowledge base and exchange* The community is very experienced in programming and building electronic devices. It develops OEM-based solutions and provides technical assistance by answering questions in the forum quickly and reliably. The forum discussions are characterised by a particular depth of knowledge that makes it difficult for outsiders to join in.	*limited knowledge development and difficult knowledge transfer* The community is concerned with building local recycling ecosystems. Besides developing simple tools for material processing, it also deals with organisational issues, such as the procurement and sorting of plastic waste, public relations, financing and management of volunteers. The online forum serves primarily as a source of inspiration and general information, as clarifying technical questions is difficult.
Entrepreneurial experimentation (EE)		
encouraging (entrepreneurial) experimentation with geo-data Free data lowers the barrier for commercial and non-profit actors to experiment with geoinformation services. By making the data publicly available, the community encourages competition for new ideas and the testing of alternative applications.	*(limited) contribution to reducing technological uncertainty* Community members experiment with DIY solutions at home or use the technology for educational purposes and research. Documentation of actual implementations reduces uncertainty by providing proof of feasibility. However, documentation in the forum is unsystematic and incomplete.	*demonstration of feasibility through project documentation* The community demonstrates the feasibility of local plastic recycling with its worldwide projects documented at the PP website. Online tutorials, videos and pictures encourage practical implementation. Economic viability and legal compliance remain uncertain.
Influence on the direction of search (IDS)		
influence through collection and bundling of user preferences As a rule, the OSM Foundation does not decide on issues of content. Contributors decide which topics are dealt with and in what form. As a result, the community bundles the interests of the users, points out unmet demands and addresses them. Disputes over direction are part of the basic democratic understanding of the community, and there are concerns about the growing influence of market participants within the community.	*reiteration and improvement of de-facto standards* OEM builds on basic technical components that represent de facto standards. The technical base is constantly expanded and improved. Beyond that, there are hardly any regulating or coordinating elements. The forum is focussed on technical issues, there is no collective action and hardly any exchange about common goals and values.	*long-term influence through awareness and capacitation* With its campaigning, PP raises public awareness and puts pressure on industry to improve the recyclability of plastic products, even if the processing techniques developed are not applicable on a large scale. The knowledge and experience of the community help pioneering manufacturers to improve product design and the use of recycled materials in production.
Market formation (MF)		
stimulating 'user-complemented' downstream markets of geoinformation services Business activities have developed out of the community, with a common model being that community members offer commercial consultancy services. The interviewees report on logistics companies, digital apps and platforms, delivery services, railway companies and car manufacturers that rely on OSM data.	*no significant demand outside the tech-savvy niche* Apart from the sale of components or starter kits to facilitate self-provision of community members, there is no evidence of significant business activities commercialising innovations of the community, so far. Marketing would require technical simplification and investments in making products more user-friendly.	*establishing a green premium market* PP supports the sale of tools, raw materials and recycled products with an online bazaar. Micro-enterprises, designers and artisans successfully use PP innovations to manufacture and sell plastic products with a green premium (e.g., plastic tiles or flipflops). With functioning recycling systems, large-scale use makes neither economic nor ecological sense and often even violates legislation.
Legitimation (LEG)		
widespread use by diverse actors promotes general acceptance OSM is well known and used by numerous actors, including large and established companies (roughly on par with Google Maps). The wide use by commercial and non-profit actors as well as academics contributes to the general acceptance of the technology.	*no legitimation activities other than technical improvement* Widespread adoption would require a change in policy frameworks or consumer behaviour which is however not addressed by the community. OEM focusses on technical improvements to create legitimacy indirectly.	*raising awareness and enhancing the value of plastic waste* PP advocates the recycling of plastic. It cooperates with environmental initiatives and NGOs to promote the idea of a circular economy. Technical solutions and products are presented at educational workshops, trade fairs, round tables and public events.
Resource mobilisation (RM)		
mobilisation of voluntary and paid contributors To a large extent, the activities of the OSM community are driven by volunteer work. However, due to growing commercial interests, paid contributors are also increasingly active. In addition, donations are raised, which are mainly used to run the server infrastructure. Another source of funds is in the area of humanitarian aid.	*no additional resources of substantial scale* The community does not actively outreach to new members. Some find their way to the community through the use of technology in higher education. However, the barriers to entry are relatively high for outsiders (not least because of the language).	*mobilisation of volunteers and (public) funding* PP mobilises environmentally concerned, anti-consumption and post-growth volunteers and public funding. It reaches a broad target group of young people who often get involved in the context of scientific or student projects. Some activities are financed by prizes and donations. In addition, PP raises public funds for environmental education.
Development of positive externalities (PE)		
free use of geoinformation and processing tools The provision of a shared resource, the geospatial information database, is the central	*free deep-end support for technical implementation* By providing technical assistance and sharing their own knowledge and experience in the forum,	*free practical know-how and marketing support* The community supports initiatives that build local plastic recycling ecosystems with practical

(*continued on next page*)

Table 5 (*continued*)

OSM	OEM	PP
concern of the OSM community. This creates benefits for potential users and attracts participation from stakeholders not only in the community but across the geo-information services sector.	contributors support other users of the technology. This support service is available to interested parties free of charge. However, the application is still limited to the hobby and education sector.	know-how, open-source blueprints, a recognisable brand and an online marketplace for selling green premium products. This helps interested people to get involved and to become entrepreneurs in this field, to take up the ideas of the community and develop them further.

explain that such problems are usually solved locally. In contrast, OEM participants interact mainly online and perceive themselves primarily as users of an online forum. Despite all due caution in interpreting the forum data, important characteristics of the communities are reflected in the networks of the observed online interactions.

A first obvious difference between the communities can be found in the general content structure of the online forums, when distinguishing between technical and organisational issues (Table 4). The high proportion of technical topics in the OEM forum confirms the 'tech community' character, while the relatively high proportion of organisational topics underlines the strong community orientation of 'grassroots innovation' in the PP forum. Since 90 % of the exchange in the OSM forum takes place in national subgroups of different languages whose content we cannot reliably categorise, the high degree of decentralisation of OSM as a 'crowdsourcing' community becomes particularly clear.

The communities studied seem to differ significantly regarding the diversity of their members and their openness for new and unexperienced contributors. The OEM community is perceived by interviewees as relatively homogeneous and inaccessible. In contrast, OSM and PP members report a very large number of sporadic volunteers. According to these assessments, OEM and PP seem to be at the opposite ends of a spectrum that ranges from homogeneous and closed to diverse and open communities, whereas the OSM community is located somewhere between these extremes: on the one hand, it is very diverse, strongly internationalised and open (especially in the field of mapping), but on the other hand it is very much segregated into national groups. Considering that socio-economic profiles of forum users are usually not available or inconsistent, the proportion of casual contributors (ranging from more than half for PP to less than a quarter for OEM) seems to be a reasonable indicator for a community's diversity and degree of openness, which can be retrieved directly from the contributor network formed by the forum data.

Another distinguishing feature is the degree to which communities are coordinated. A possible indicator is the proportion of the largest subgroup of the network in which all contributors interact. This community metric is largest in PP and smallest in OSM, which is consistent with PP being relatively centralised, with the core team around Dave Hakkens making important directional decisions and a small group of so-called ambassadors having particular influence on the further development of the community. In contrast, the OSM community is highly decentralised and divided into largely autonomous local subgroups that are only loosely coordinated by the OSM Foundation. The OEM community is positioned in between: no group of contributors - apart perhaps from the founders - stands out as being particularly influential.

Finally, communities can be differentiated according to their collaboration behaviour. The extent to which members of a community take on tasks to organise and further develop the group has been proposed as a distinguishing feature of online collaboration patterns (Haythornthwaite, 2009). According to this classification, communities can be located on a spectrum between rather anonymous and independently acting 'crowds' and the building of personal status and group-oriented 'communities'. The network density may be indicative of a stronger community orientation, but it is only in the overall view of the network metrics and the qualitative assessments from the interviews that a clear picture emerges of the prevailing collaboration patterns.

The pronounced 'community' character of PP is evident in the great importance of organisational topics in the online forum, the high network density and the relatively large group of highly interacting contributors. It can be underpinned by countless interview statements that show a high level of identification with the community. In contrast, the 'crowd' character of OEM is reflected in the low network density, the decentralised and anonymous network structure as well as in interview statements that negate the existence of shared values and goals. OSM again shows an ambivalent character, where a strong community orientation seems to prevail amongst the (software) developers coordinated by the OSM Working Group, while anonymity and crowd behaviour characterise the online collaboration of the majority group of (often casual) mappers. This finding is also very much in line with previous research on this

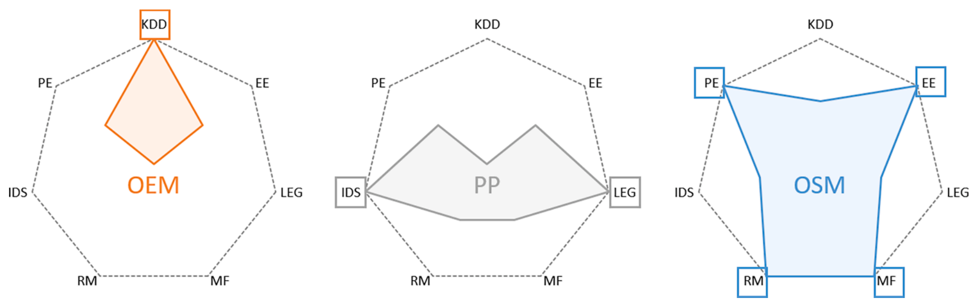

Fig. 2. Community profiles of TIS contributions.

community (Budhathoki and Haythornthwaite, 2013).

4.5. Analysing the TIS contributions of the three user communities

Table 5 summarises for each community the assessment of their contributions to the respective TIS derived from the interviews with community members. As a result, different functional profiles of the communities can be identified.

Each of the communities studied influences the technological innovation system in its own ways, but contributions to entrepreneurial experimentation (EE) and the creation of positive externalities (PE) are common to all of them. We assume that TIS contribution profiles (Fig. 2) are essentially determined by the community types we described in the previous sub-section. However, as will be shown, the profile also depends on how the boundaries of the TIS are drawn, i.e. which technology is placed at the centre of the analysis.

In the field of energy monitoring technologies, OEM contributes primarily to the deepening of technical knowledge and its dissemination (KDD). It develops and shares innovative solutions for home use. The community answers user questions in the forum quickly and reliably and gives practical tips for implementation. This community support makes it easier for potential users to get started despite the lack of user-friendliness of the products and thus significantly contributes to the spread of OEM solutions. All information and ideas are available to third parties as a free resource for their own projects, but only accessible with certain prior knowledge or significant learning effort. The community helps to reduce technical uncertainties by demonstrating feasibility through a variety of examples, albeit this contribution is limited due to unsystematic and incomplete documentation, especially of failed attempts. Technical improvements are the most important contribution to the legitimacy of the focal technology. But beyond the narrowly defined TIS boundaries, the provision of home solutions for energy monitoring has stimulated the uptake of renewable energy and heat pumps in the domestic sector (Hyysalo, 2021).

For the PP community, technology development is only a means to an end. From a technological point of view, the proposed solutions are unspectacular. The machines developed by the community are deliberately simple and easy to reproduce. The main contributions to innovation in the field of plastic recycling are therefore social rather than technical. Above all, the community creates legitimacy (LEG) and influences the direction of the search for solutions (IDS) when it raises awareness of the associated environmental issues, advocates for closing material loops and demonstrates the feasibility of local recycling ecosystems. With the online forum, the community encourages local projects worldwide to be inspired by and benefit from the wealth of experience documented there. These projects experiment with alternative social practices and develop appropriate small-scale solutions. With educational workshops and media campaigns, PP lobbies against the unsustainable use of plastic and pressures manufacturers to set up return systems and improve product recyclability. In doing so, PP is relatively successful in mobilising volunteers who invest a considerable amount of time, and in tapping various sources of funding, ranging from private donations and public funding to prize money and sponsorship by industrial companies, as well as in setting up small businesses for green premium recycling products with fashionable designs.

The most comprehensive spectrum of contributions to TIS functions is shown by the ‘crowdsourcing’ community OSM, which above all is about creating a public resource. While the community develops new software tools for the collection and processing of crowdsourced data, its most important contribution to innovation is arguably in the provision of geospatial information for free (PE), which in turn encourages entrepreneurial experimentation (EE), attracts volunteer work as well as business investment (RM) and fosters the emergence of novel applications in the field of geo-information services (MF). The wide use of OSM data by a variety of actors, including large companies and governments, gives it legitimacy. By engaging in areas of unmet needs, the community indirectly exerts a steering effect on innovation. For example, new maps and applications are created for cyclists because many volunteer mappers contribute specific information to the database for this purpose.

Although all three communities studied contribute differently, the case studies show that online user communities can contribute to the entire spectrum of TIS functions. Most notably, our findings show that they fulfil multiple tasks beyond the creation of technical solutions, ranging from the pooling of information about the innovation to legitimisation and marketing support.

5. Discussion and policy implications

The case studies have shown that online user communities contribute to technological innovation systems in several ways, corroborating their potentially vital role for sustainability transition processes that has been suggested by the literature. From a TIS perspective, these communities help reducing technological uncertainty, legitimise alternative solutions, and contribute to the formation of markets for more sustainable technologies. No intention is needed as "they inadvertently provide indirect support by doing what they do" (Hyysalo, 2021). Moreover, community members may not even be aware of their contribution to the innovation system.

It has been argued that user communities can become transition intermediaries that help to pluralise and ‘open up’ alternative innovation trajectories beyond pathways explored by incumbents (Hyysalo, 2021; Kohtala, 2017; Smith et al., 2016). We found evidence that they both generate new ideas and products by enabling and encouraging users to come up with new solutions, but also contribute to the implementation and wider diffusion of these innovations by providing practical information for their adaptation and use, by supporting exchange and peer learning and by helping to reach out to mainstream actors, which underlines their importance as transition actors.

It is fair to say that in user communities such as the OEM community, niche players experiment and tinker with new technical solutions. Some of them integrate these solutions into their daily lives, adopt and adapt the focal technology, as well as the associated usage practices and routines. Sharing individual experiences provides information on the preferences and needs of users, the suitability of the proposed solutions, and common obstacles to their practical implementation. This helps to reduce technological uncertainty and reveals use potentials and business opportunities. Although the OEM members we interviewed showed little ambition to commercialise their ideas, the knowledge gathered by the community could become valuable for marketing the technology as the framework conditions change.

The technological niche fortifies as niche actors learn from each other, develop common practices and tools, like in the case of the PP community. The exchange with peers helps them to align their interests, create meaning and a shared understanding of what the technology is about. The community supports its members in advocating for their niche by providing them with information, meaningful interpretations, purpose and reasons for their activities, and even with agitation material. A shared vision helps them joining forces with broader social movements, collaborating with mainstream actors or calling for necessary changes at regime-level. The PP community can be seen as a boundary object that allows different types of actors (activists, educators, micro-entrepreneurs, plastic manufacturers) to find their stake in advancing the technological niche. In this way, the PP community advances sustainable solutions and reaches out into the mainstream to disseminate ideas and practices.

The OSM case demonstrates the ability of user communities to mobilise voluntary labour on idealistic grounds to keep the niche competitive with established actors, at least temporarily, while exerting pressure for change at regime level. It has also managed to attract mainstream actors and to generate income for some community members by enabling market applications of the niche technology. Apparently, the OSM community has succeeded in reconfiguring the socio-technical system, as the once niche technology is now used by mainstream commercial and public actors and is being further developed according to the rules of the community.

The evidence also confirms the literature that stresses the important role of online communities as trans-local networks (Grabher and Ibert, 2014) and as user-side intermediaries (Hyysalo et al., 2018). While in early phases of the transition to sustainability their contribution to creating diversity, exploring alternative solutions, sense-making and coordinating niche activities can be of particular importance, in later phases the wider circulation of knowledge, the alignment of interests of diverse actors and finally the social anchoring of niche practices become important.

It is of course interesting to speculate how these contributions are related to the observed community characteristics. One may for example argue that the primary contribution of technically focussed crowds is the production of new knowledge which can help push forward technological developments in directions which may differ from the innovation trajectories pursued by incumbent, commercial actors. In that sense, such communities may 'open up' new possibilities which is an important process within transitions. More politically oriented communities may contribute more to social embedding of new technologies or practices which is also an important process within sustainability transitions (see e.g., Barnes, 2019).

Arguably, the impact that user communities have on the development of sustainable niches is conditioned by their network characteristics. For example, the composition of the community can affect trust and understanding amongst its participants, and thus the quality of interaction (Frey and Lüthje, 2011). In the literature, diversity in terms of gender and nationality (Beretta, 2019; Ortu et al., 2017), orientations and user roles (Freeman, 2007; Fuger et al., 2017; von Krogh et al., 2012) is often associated with greater reach and impact. The OEM case illustrates a certain trade-off: on the one hand, the homogeneity of the community seems to facilitate technical exchange, but on the other hand, it possibly limits the further dissemination of its ideas and practices and its ability to involve other actors.

The innovation literature attaches particular importance to the central and well-connected members of a community (Dahlander and Frederiksen, 2012; Resch and Kock, 2021). In the PP case, this could also be linked to a trade-off: prominent members, such as community ambassadors, who voice criticism of excessive consumption and further growth of the industry, increase the visibility and positioning of the community, and thus promote the mobilisation of volunteers, but perhaps also limit its quality as a boundary object and thus its bridging function in the long term. Recently, the distribution of power amongst innovation actors has come into focus of research on innovation and social change (Avelino, 2021). The case of OSM illustrates how power distribution plays out in online communities: While the strong decentralisation in the OSM community leads to frictions that can slow down development, it also seems to be accompanied by a greater openness to collaboration with established actors.

Given the urgent need for sustainability transitions and given the diverse and positive contributions to innovation processes outlined above, we argue that policy makers should provide targeted support for communities which contribute to such transitions. From many transition studies we know that it is often not the technological developments which are difficult or lacking, but the wider processes of socio-technical reconfiguration which are difficult to accomplish. Of course, such an 'instrumental' perspective on the role of (user) communities would be highly contested in the literature on grassroots innovation (Ornetzeder and Rohracher, 2013; Seyfang and Smith, 2007; Smith et al., 2014). Nevertheless, such a view could help to attract more attention and support for collaborative user innovation from the policy side which is timely given the broader definition of innovation by the OECD and the need for a transformative innovation policy (e.g. Haddad et al., 2022).

Torrance and Hippel (2013) have long called for greater awareness of the existence and value of user innovation and to protect what they call "innovation wetlands". They have shown that, in practice, legislation can, out of ignorance, unreasonably restrict the freedom of users to innovate and to collaborate. We believe that our revision of the TIS framework helps to better assess the role user communities and other informal actors play for innovation and sustainability transitions. This is an important step forward, because only if we can systematically identify, critically analyse and document the capacity of such actors to contribute to innovation and broader transition processes can we make a case for protecting (and perhaps even supporting) such actors and activities, which have so far not been in the focus of traditional innovation policy, despite the changes in the OECD definition of innovation (OECD, 2018). Given the potential impact of digital commons on socio-technical change towards sustainability, public support for collaborative user innovation currently seems underdeveloped, but is also far from straightforward.

Classic innovation policy instruments, such as the granting of intellectual property rights, can limit collaborative user innovation by exposing user innovators to the risk of (unintentional) patent infringement (Strandburg, 2007). To facilitate the free use and exchange of innovation-related information by user communities, the extension of "fair use" rights and other forms of liability protection have therefore been proposed (Baldwin and von Hippel, 2011). Other support options include opening up public resources to unlicensed use and experimentation, interpreting regulations more generously or granting legal exemptions, as well as explicitly considering how legislation affects informal innovation activities in regulatory impact assessments (von Hippel, 2017, 2005).

Direct funding of (sustainability-oriented) innovators within such communities is difficult if they do not perceive themselves as actors eligible for government support (Franke et al., 2016). In addition, standard accountability requirements of innovation programmes often pose too high administrative hurdles for casual actors. Moreover, such support should allow the community to remain independent and self-determined, which is important for the community members and their motivation to participate. This means that providing support should be done in a way which does not amount to a 'strong' intervention. Adequate measures for the promotion of such bottom-up innovation processes, designed in such a way that they do not crowd out intrinsic incentives, as well as appropriate eligibility criteria and evaluation instruments, have yet to be developed and tested.

However, there are some studies which point to some potential ways forward. For example, easily accessible funding through micro-grants have been argued to be needed to support user innovation, including micro-grants for the establishment and operation of communities and forums (Hyysalo et al., 2013), as their collaboration relies on technical and institutional infrastructures, the provision, operation and maintenance of which involve significant costs. Hyysalo et al. (2013) has emphasised the importance of moderators for community exchange in online discussion forums and the need for nominal support to cover running costs. Of course, paying community moderation and management can also be problematic if they are perceived as "gatekeepers" rather than community promoters.

Supporting innovation ecosystems for users without limiting their self-determination requires a genuine willingness on the part of public authorities to relinquish control and governance. This can become a delicate balancing act when users experiment on the edge of legality, for example with the use of psychedelic substances (Söderberg et al., 2016). With regard to users experimenting with sustainable practices, this seems to be far less problematic, but of course tensions with established legal provisions can arise here as well. In this case, it could make sense from a sustainability perspective to rather adjust the existing rules in favour of the bottom-up solutions, thereby putting pressure on the established socio-technical system and creating windows-of-opportunities for a broader diffusion of the niche technology (Seyfang and Smith, 2007).

Hyysalo et al. (2017) have highlighted inadequate documentation as one major problem for the diffusion of innovative user solutions in sustainable energy technologies. In fact, defining and adhering to minimum project documentation requirements that allow for easy replication remains a challenge for the open hardware sector in general, which has been newly addressed with the development of the DIN-Spec 3105 standard (Bonvoisin et al., 2020). The development of new digital support tools, such as semi-automated CAD-coupled documentation (Mariscal-Melgar et al., 2023), could soon greatly facilitate the creation and updating of assembly instructions by user innovators.

The provision of the necessary technical tools and infrastructures for collaborative user innovations - from digital exchange platforms, repositories and collaboration tools to physical makerspaces - as public education services could be justified on the grounds that digital commons support the broader moves towards more democracy, transparency and citizen participation in science, politics and public administration. Universities and libraries would be excellent places for setting up open laboratories and workshops (makerspaces, fablabs, hackerspaces), which have been shown to increase user innovation and diffusion rates (Halbinger, 2018), foster local entrepreneurship (Cuntz and Peuckert, 2023) and promote a sustainability-oriented (critical) maker culture (Kohtala, 2017). The science community has often been the starting point and main beneficiary of open-source-developments (Pearce, 2012; von Hippel, 1976). A standard use of open source tools in science and education would not only increase the comparability and reproducibility of research results, improve access to data and knowledge by citizens, but also provide important impulses for user innovation ecosystems. If it were not for the lack of qualified personnel in public administration, preferential procurement of open source technologies could represent an interesting option for cities and municipalities to support the dissemination, testing and further development of open source solutions, while fostering transparency and vendor independence in the public sector.

6. Conclusions

This paper started from a broad understanding of innovation beyond firms and formal R&D, building on ideas from the user innovation, peer production and digital commons literature, and suggesting that online user communities have given rise to a new mode of collaborative technology development based on digital commons. Utilising the functions of technological innovation systems approach, we empirically analysed three open-source communities to assess how they contribute to technological innovation and wider socio-technical change.

Our empirical contribution is to show how such actor networks vary significantly in terms of member composition, power distribution and community orientation. Regarding the contribution to the emergence and development of technological innovation systems, we found that their activities affect a wide range of TIS functions, albeit with large differences in the functional profiles of the communities studied. The cases analysed range from strongly technology-oriented, rather anonymous networks to very broad-based communities that aim to influence political discourse, public acceptance, and the social embeddedness of technologies. Our case studies inductively identified quite different types of user innovation communities ranging from 'tech community' to 'crowdsourcing community' to 'grassroots innovation community'. These are preliminary observations that cannot be generalised due to the small number of cases studied, but it should be further investigated in follow-up studies whether these are archetypes of some kind and whether there are additional types of user communities. We have also discussed how the characteristics of these communities may shape their contributions to sustainable innovation processes.

Our theoretical contribution is to re-conceptualise TIS functions and operationalise them as a useful framework for assessing how online user communities contribute to TIS development. This is in line with recent suggestions by Bergek (2019), who argues that there is a need for more qualitative, in-depth analysis of the mechanism underlying TIS functions and a wider range of actors (user communities in our case). We demonstrate that the approach can be applied to a broader range of innovation actors than is usually the case in such research (which often focusses on firms, traditional R&D actors such as public and private labs, universities, start-ups, etc.). Our new conceptualisation integrates insights from the literature on user innovation, peer production and digital commons taking into account the motivations, orientations and dynamics associated with actors in the household sector. In doing so, we maintain the standard assumption of the TIS literature that the contribution to the development of the innovation systems does not have to be intentional to be effective.

An important topic for future research would be to further develop the inductively derived typology of different types of 'user innovation communities' though additional, in-depth studies of different communities, to further reflect on whether and how policy support could be targeted for different types of communities, but also how such policy support would need to take into account the respective phase of the transition in a given socio-technical system (such as pre-development, acceleration and stabilisation).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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