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Article

Opening up science for a sustainable world: An expansive normative structure of open science in the digital era

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Abstract

New digital technologies and tools, together with evolving open physical and digital infrastructures, are remodelling science and innovation practices at universities and challenging their existing cultures, cognitive norms, missions, and policies. The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions, and technologies for sustainable development. The results of this study provide novel insights and important suggestions to guide the advancement of open science and innovation policies at universities for a sustainable economy, society, and environment—in sum, for a sustainable world. We infer a new expansive normative structure—practices, norms, and institutional goal—for open science and a new role of researchers in the digital era. Based on our findings, we propose an expansive model of university research and innovation to guide the renewal of university governance in the digital era.

Key words: open science; open innovation; sustainability; openness; research teams; university; science policy; innovation policy

1. Introduction

Open science is the science ahead. Open science in the digital era is 'transparent and accessible knowledge that is shared and developed through collaborative networks' (Vicente-Saez and Martinez-Fuentes 2018: 434). The grand societal challenge we are facing with SARS-CoV-2 to ensure healthy lives and promote well-being for people of all ages can only be solved through new levels of integration, new science practices, and new mechanisms for global collaboration among all participants in research, from performing, contributing to, and using research to defining problems and solutions in research. The same applies to the global challenges of ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all or taking urgent actions to combat climate change and its impacts. Forefront technological breakthroughs empowered by big data, artificial intelligence, the Internet of Things, machine learning, synthetic biology, 3D printing, blockchain, and quantum computing are producing unprecedented possibilities as well as challenges to instantly, interactively, collaboratively, and responsibly perform science (Nielsen 2011; Owen et al. 2012; Bogers et al. 2018) that addresses society's grand challenges. These include, among others, the grand challenge of how to accomplish the urgent Sustainable Development Goals that the United Nations has set for 2030 (Wolkovich et al. 2012; Fiore et al. 2018; Global Sustainable Development Report 2019).

Openness in science entails the principles of transparency, accessibility, authorization, and participation, which underlie science practice (Vicente-Saez et al. 2020). These principles indicate which aspects of the anatomy of open science are, in fact, open in the digital era. Examples of more recent open science practices adopted by research teams include open data, open labs, crowdsourced practices (Fecher and Friesike 2014), and transdisciplinary research practices (OECD 2020) to share and develop scientific knowledge among researchers, citizens, research institutes, companies, non-governmental organizations (NGOs), municipalities, states, and international organizations. The increase in the use of digital technologies and tools and open physical and digital infrastructures for researchers' science inquiry is enabling the transformation of the social institution of open science in the digital era. Digital technologies and tools and open physical and digital infrastructures are challenging existing science and innovation cultures, practices, cognitive norms, missions, and policies at universities. It is important to acknowledge that these technologies are also remodelling science and innovation practices at universities to develop actions, solutions, and technologies for societal grand challenges.

Sustainability research is a young and transdisciplinary research field and is also a pioneer in open science and innovation practice development at universities (i.e. Tai and Robinson 2018; Zipper et al. 2019). Through forerunner global, regional, national, and local collaborative research projects and initiatives in sustainable development, researchers are testing new scientific practices. The field of sustainability

research is establishing new interactions and processes among academia, citizens, and policy-makers (Hecker et al. 2018).

The purpose of this empirical study was to understand how existing and recently adopted open science practices and the underlying principles and attitudes of research teams support the advancement of knowledge and the development of actions, solutions, and technologies for sustainable development. We also wanted to understand the challenges research teams have encountered when adopting novel open science and innovation practices. We studied 23 research teams at Aalto University in Finland from the disciplines of science, engineering, art, design, architecture, electrical engineering, and chemical engineering that perform research and innovative work that addresses the grand challenge of combating climate change and its impacts. The specific objectives of our study were to first expose how the four dimensions of openness in science—transparency, accessibility, authorization, and participation (Vicente-Saez et al. 2020) —were present and how their levels of openness were formulated in research teams working on sustainability, specifically in the area of climate change. Second, we aimed to identify commonalities as well as distinctive features in open science practices adopted by research teams working on climate change issues. Third, we analysed both the efficiencies gained and the key challenges prevalent in opening up science encountered by research teams. Finally, we aimed to identify open science practices' impact on the role of researchers and their teams when researching and developing actions, solutions, and technologies for sustainable development.

The results of this study provide novel insights and important suggestions for directions on how to guide the advancement of open science and innovation policies at universities for a sustainable economy, society, and environment—in sum, for a sustainable world. First, we infer an expansive normative structure of open science among researchers working on sustainability, including institutional goal, norms, and practices enabled by actively using digital technologies and tools and open physical and digital infrastructures. Such a structure is key for designing and fostering efficient science policies in the digital era. Second, we reveal a major update in open science practices that has occurred in sustainability research among forerunner research teams. We identify how open data practice has radically transformed university research teams' processes of collecting, evaluating, and circulating data and designing and performing scientific studies. We also identify how transdisciplinary research practice by research teams has enlarged their research process in terms of academic and societal engagement and collaboration by recognizing and including new participants in every stage of the research process. Finally, we reveal how the new academic entrepreneurial ethos embracing open science norms and practices that we observed among many of the research teams is contributing to the evolution of the role of researchers and, with it, the traditional process of knowledge value creation and transfer—the innovation process—in the digital era. We conclude the paper with a discussion of the implications for the governance of research and innovation in the digital era at universities.

The article is organized as follows. We present the theoretical framework on open science, sustainability, science policy, and university governance in Section 2. In Section 3, we describe the methodology of the study. The findings of the study are presented in Section 4. In Section 5, we present a discussion of the findings and their theoretical implications for research on open science and practical implications for university leaders and science and innovation policy-makers.

2. Open science and sustainability in the digital era

The foundations of the modern or open science institution emerged with the ideals of the scientific revolutions of the late 16th and 17th centuries in Western Europe (Merton, 1938, in Merton 1973; David 1998). The prior development of printing technology and new physical infrastructure enabled scientists' adherence to new principles and practices for disclosing and disseminating new discoveries in scientific journals, in informal networks of correspondence, open demonstrations, and exhibitions. These new principles and practices challenged the social conventions as well as the incentive systems and organizational structures for performing science in that era (David 2001, 2014). Openness founded on reason and the sharing of scientific knowledge led to the first open science paradigm. In the evolving digital era, the increase in the use of digital technologies and tools and open physical and digital infrastructures for researchers' science inquiry is enabling the transformation of the institution of open science. Open science has come to encompass a wider definition of 'transparent and accessible knowledge that is shared and developed through collaborative networks' (Vicente-Saez and Martinez-Fuentes 2018). The openness of the institution of open science in the digital era goes beyond disclosing and disseminating knowledge among scientists of the first open scientific paradigm. It includes collaborative networks of participants in research (scientific, professional, and amateur users of scientific knowledge) in the pursuit of both sharing and producing knowledge. Openness in science in the digital era hence follows two dynamics: openness in sharing and openness in producing knowledge (Vicente-Saez and Martinez-Fuentes 2018). Understanding how these two dynamics of openness in science are redesigning and reopening the open science institution's foundations is highly important for effectively articulating this social institution in the digital era while simultaneously encouraging social, economic, and human progress. Novel open science practices, *technical methods* such as open data, open protocols, participatory design, and transdisciplinary research practices are currently expanding the *institutional imperatives* that synthesize the ethos of science, the norms of openness (Merton, 1942 in Merton 1973), to wider audiences and participants in science making (Vicente-Saez et al. 2020). Openness in science in the digital era involves the principles of transparency of science outputs, accessibility of science outputs, authorization in science production, and participation in science production (Vicente-Saez et al. 2020). Updating the *institutional goal of science*—'the extension of certified knowledge' (Merton, 1942 in Merton 1973: 270)—by understanding the interrelationship between the new open science practices and norms of openness in science in the digital era is key for designing and fostering efficient science policies, for redesigning efficient research systems, and for guaranteeing independent and reliable science-based institutions for all.

The practices that become norms are continuously evolving, alongside researchers' role and researchable questions' nature. This process is especially notable in the research

field of sustainability, particularly in relation to societal grand challenges such as combating climate change and its impacts. Sustainability research is a young and transdisciplinary research field that is also a pioneer in open science and innovation practice development at universities (i.e. Tai and Robinson 2018; Zipper et al. 2019). Sustainability research is establishing new interactions and processes among academia, citizens, and policy-makers (Hecker et al. 2018). These interactions among different participants in research are opening up avenues to researchers to explore a variety of new roles and scientific practices for knowledge sharing and production (Saarela 2019). Researchers' role in sustainability is gradually evolving to be more participative and collaborative (i.e. Tai and Robinson 2018; Zipper et al. 2019). Sustainability and climate change are complex economic, environmental, political, sociological, and technological phenomena that interweave with many issues of society and nature (Tai and Robinson 2018). Currently, strong and urgent societal demands seek to solve these issues by overcoming the traditional tensions of scientific openness in science–society relations (Hartley et al. 2018), going beyond normative research agendas, promoting neutrality and objectivity, and sharing and developing new scientific knowledge. Modern or open science shaped the modern world (Daston 2017) and, in the digital era, the open science institution has the potential to shape a sustainable world.

In the past, open science has dared to question the authority structure of scientific institutions such as universities in accordance with the economic, political, sociocultural, and technological constructs of the period (Redner 1987). Emerging open science practices adopted by researchers in the evolving digital era are challenging universities' second mission—research—and their third mission—knowledge and technology transfer. These emergent practices are challenging ingrained science and innovation university mindsets, cognitive norms, practices, structures, and policies to engage in solving societal grand challenges, such as sustainability and climate change. On the one hand, these new open science practices are currently contributing to the evolution of the traditional knowledge creation process, the research process (Mukherjee and Stern 2009; Lang et al. 2012; Mauser et al. 2013). Understanding how the new open science practices impact and transform the established knowledge creation process at universities is fundamental to developing open science policies in the digital era. On the other hand, these new practices and principles of openness in science are shaping openness in innovation (Vicente-Saez et al. 2020). Equally, open innovation practices and principles are shaping open science (Chesbrough 2015; Friesike et al. 2015; Beck et al. 2020). Understanding how the new open science practices impact and transform the established knowledge value creation and transfer processes—innovation process—is key for developing new university governance models and updating their research and innovation governance mechanisms. Universities, traditional open science institutions from the Enlightenment (David 2004), such as public research institutes, and more recent open innovation institutions (Perkmann and West 2014), such as research partnerships, are encouraged to deconstruct their foundations (Perkmann et al. 2013; Smart et al. 2019). Universities need to re-examine their missions, aiming to strengthen their research and innovation capabilities by harnessing new open science practices' potential in the digital era.

3. Methodology and data

We set out to study how and to what extent existing and recently adopted open science practices and the underlying principles of research teams at universities support the advancement and development of solutions for sustainable development. We conducted a qualitative empirical research study (Gephart 2004; Edmondson and McManus 2007; Bansal et al. 2018) using thematic coding and analysis (Fereday and Muir-Cochrane 2006; King and Brooks 2018a) with a hybrid process of inductive and deductive analysis to analytically explore and capture the richest features of the data. Thematic analysis is a broadly used research method for studying, characterizing, and finding patterns in rich data collected from individuals' 'own words or actions or observable aspects of [their] life in an organization or culture' (Boyatzis 1998) of complex phenomena (Daly et al. 1997; Fereday and Muir-Cochrane 2006). Studies applying thematic coding and analysis of practices have been conducted, for example, on SMEs' corporate social responsibility activities (Baden et al. 2011), primary care trust policies and practices (Richardson et al. 2009), and strategic decision-making in IT projects (Alkhuraiji et al. 2016). We use the thematic coding and analysis steps outlined by King and Brooks (2018a).

We studied the practices of 23 research teams at Aalto University in Finland during 2019 from the disciplines of science, engineering, art, design, architecture, electrical engineering, and chemical engineering. All the teams we studied perform fundamental applied research and innovation work that address the grand challenge of combating climate change and its impacts—the UN's Sustainable Development Goal 13. We conducted semistructured interviews with research team leaders. We also made observations of the research teams' physical and digital workspaces, labs, and tools.

We built on the recent open science practice typology developed by Vicente-Saez et al. (2020). Hence, when analysing our qualitative data from site visits and interviews, we first performed a template analysis (King and Brooks 2017, 2018b). Exposing similarities and differences in open science practices by research teams is important for understanding the underlying mechanisms that shape teams' open science and innovation practices at various levels, including the team and its leader, the research discipline, university governance, and national policies and programmes.

3.1 Research teams studied

Finland and Aalto University are excellent locations to study the open science practices of research teams that are working on topics related to developing solutions for a sustainable future. Finland has been a forerunner in the European Union (EU) in promoting open science and innovation and has recently been proactive in opening up public data and creating open research infrastructures. Finland is committed to promoting openness as a fundamental value and integrating open science practices into researchers' everyday work, as stated in the Finnish Declaration of Open Science and Research 2020–2025 (Finnish Learned Societies

2020). Finland has a strong reputation as a country spearheading sustainable development (Kepa 2017). Fully in line with Europe's vision and consistent with EU policies, Finland is playing an active role in implementing the 2030 UN Agenda for Sustainable Development at the national level and internationally. Accordingly, in its climate policy, Finland advocates for the implementation of the Paris Agreement and recognizes climate's social, economic, and environmental dimensions to promote a carbon-neutral welfare society (Publications of the Prime Minister's Office 2020). In this context, the role of Finnish researchers in sustainability—such as forest bioenergy, a very polarized area with regard to carbon-neutrality and biodiversity sustainability—is gradually moving from 'pure scientists' towards more 'participatory knowledge producers' (Saarela 2019).

Aalto University was able to shake off some of the institutional inertia of universities when it was founded as part of a university regulatory reform in Finland in 2010. Aalto University arose from the merger in 2010 of a business school, a technical university, and an architecture, art, and design university. The current university mission, articulated in 2019, is bold. Aalto University states that its mission is to renew society with research-based knowledge, radical creativity, and an entrepreneurial mindset. The university promotes the creation of novel open physical and digital spaces as well as practices that encourage breakthroughs in and across science, art, technology, and business. An explorative culture is empowered in several ways, such as through internal funding, personnel allocations, and recognitions (e.g. awards). One of the key rationales for the active support of an explorative culture is the goal of pioneering innovative solutions for a sustainable world (Aalto Living Strategy 2020). Sustainable development is the 'ethos' of Aalto's strategy and values. In line with Aalto's mission, the university has recently jointly founded the University Network for Innovation, Technology and Engineering (UNITE!), a European University Alliance composed of seven European universities. UNITE! aspires to generate innovative, feasible, and effective solutions to global challenges in line with open science principles and practices (UNITE! Mission Statement 2019).

We studied 23 research teams to understand how existing and recently adopted open science practices and the underlying principles of research teams support the advancement and development of solutions for sustainable development. We explored and analysed scientific research and artistic activities conducted in the research groups at the School of Arts, Design and Architecture, School of Chemical Engineering, School of Electrical Engineering, School of Engineering, and School of Science to select our sample. We included research teams whose research focus was climate change mitigation technologies and solutions as well as research and artistic activities that contribute to raising awareness. We further ensured that the sample of 23 research teams included a representative variance of research teams with respect to the openness of their research practices with respect to the four open science dimensions (see Table 1). These selection criteria ensured richness in the observations and rigor in finding commonalities and explainable differences (Tracy 2010). Our sample is a solid, descriptive, and scalable representation of the Finnish and EU context for the accomplishment of the 2030 UN SDGs Agenda. These research teams, comprised of small to medium size groups of early career and consolidated researchers, are neutral representatives of their area who are working on sustainability research. They are supported by university, national, and international funds. The research teams are all internationally active in conducting research, contributing to research, using research, and defining problems and solutions with collaborative networks when working on topics related to combating climate change and its impacts.

3.2 Data collection

We conducted semistructured interviews with all 23 team leaders. In addition, we conducted two informal interviews with early-career team research members (Bahlai et al. 2019) as validity check, which are included in Table 1. We developed an interview protocol to guide the collection of data during the interviews (see Supplementary Appendix 1). To guide the development of the interview questions, we used the insights and findings of Vicente-Saez et al. (2020) on the open science and innovation practices of university research teams The interview questions were open-ended to obtain the richest data possible to strengthen reliability in pattern identification during data analysis and to ensure methodological fit (Edmondson and McManus 2007). We refined and validated the interview protocol with a test group of two professors and three doctoral students at the corresponding departments of the authors. The face-to-face interviews were conducted from October to December 2019. The interviews were recorded and ranged from 24 to 59 minutes. All interviews were transcribed.

In addition to the primary data of the semistructured interviews, we made observations of the research teams' digital and physical workspaces, labs, and tools. We took pictures and videos during the visits and developed a research voice memo diary to document insights from the interviews and observations. We also collected web-based material on the scientific, innovative, and artistic activities of the research groups, university strategy documents, and most recent (past 10 years) central official policy documents on open science and sustainable development produced by the Ministry of Education and Culture in Finland—Open Science National Coordination (4), European Commission, DG Research and Innovation (6), Organisation for Economic Co-operation and Development (2), and United Nations (7). These secondary data, which were collected using different methods, ensured research credibility by means of triangulation (Tracy 2010).

3.3 Data analysis

We performed data analysis with our primary data of semistructured interviews, undertaking a thematic analysis approach to organizational research (King and Brooks 2018a) by using a template analysis style (King and Brooks 2017, 2018b). This approach helps to ensure 'credibility', 'dependability', and 'transferability' in qualitative studies (Polit and Beck 2008).

First, we started the iterative data analysis by familiarizing ourselves with a subset of the data. We selected one interview from each research discipline, five interviews in total, and one of each of the schools of Aalto, which represented a good cross-section of the data set. Second, we conducted a preliminary coding of these five interviews to start defining themes. We established four a priori themes, the four theorized dimensions of openness in science: transparency and accessibility

Table 1. Research team leaders interviewed.

Research team leaders	Title and responsibility	Name of research team and school	Research team topics
Antti Ahlava	Vice-President for Campus Development, Professor, and Research Team Leader	Group X, School of Arts, Design and Architecture	Shared resources and mixed use; sustainable development; life cycle thinking; co-design; user-centred design; value co-creation; communicative planning; parametric solutions; learning organizations and spaces
Idil Gaziulusoy	Professor and Research Team Leader	Sustainable Design Research Group (NODUS), School of Arts, Design and Architecture	Transdisciplinary research and co-creation, socio-ecological-technological system transformations; sustainability science; practice theory; self-organizing systems; participatory and collaborative design; futures studies; governance innovations
Olli Dahl	Professor and Research Team Leader	Clean Technologies, School of Chemical Engineering	Sustainable industrial processes; treatment of wastewater and industrial residues; responsible use of raw materials; development of cleantech processes; environmental technology
Bassam El Baroni	Professor and Head	Sharing and Cocreating Transdisciplinary Artworks Initiative (SCTA), School of Arts, Design and Architecture	Responsible exhibitions; transdisciplinary artworks; collections and public art. Climate was an open call to Aalto Community (artist, students, and researchers) to submit proposals about how food might help us to understand the impacts of climate change
Juanjo Galán	Professor and Research Team Leader	AaltoLAND—Landscape Architecture Programme, School of Arts, Design and Architecture	Green infrastructures; ecosystem services; landscape urbanism; sustainable metabolisms; landscape characterization and assessment; the environmental, cultural, socio-economic, and sustainable dimension of the landscape
Kamyar Hasanzadeh	Researcher and Coordinator of the Open Data Initiative	Spatial Planning and Transportation Engineering Group, School of Engineering	Engineering as collaborative development; sustainable built environment; systems design; human-centred living environments; new planning and policy-making methods and processes; development and governance or urban technologies and services
Pekka Heikkinen	Professor and Research Team Leader	Wood Programme in Architecture and Construction, School of Arts, Design and Architecture	Construction for a sustainable future; energy-efficient building design; natural building materials; wood architecture and industrial building
Mark Hughes	Professor and Research Team Leader	Wood Material Technology, School of Chemical Engineering	Climate change mitigation potential of wood in construction; wood technology; wood in climate smart construction; wood in comfortable and healthy buildings; bio-composite materials
Marjo Kauppinen	Professor and Research Team Leader	Product Requirements and Architecture Research Group (Preago), School of Science	Development of digital services; requirements engineering, user-centred and service design, customer value and user experience, data science as part of digital services, software ecosystems, eHealth
Jaakko Ketomäki	Professor and Research Team Leader	Smart Building Technologies and Services, School of Electrical Engineering	Smart building; sensor networks; human-building interaction; intelligent control strategies of building systems
Harri Koivusalo	Professor and Research Team Leader	Water and Environmental Engineering, School of Engineering	Global water resource scarcity; sustainable circular economy; water and development; water resources management; environmental hydraulics; wastewater engineering
Marketta Kyttä	Professor and Research Team Leader	Spatial Planning and Transportation Engineering, School of Engineering	Engineering as collaborative development; sustainable built environment; systems design; human-centred living environments; new planning and policy-making methods and processes; development and governance or urban technologies and services
Jorma Kyyrä	Head of the Department of Electrical Engineering and Automation, Professor and Research Team Leader	Illumination Engineering, School of Electrical Engineering	Illumination engineering; electrical building services; indoor lighting, energy-efficient lighting systems; outdoor lighting; visual and biological effects of lighting; lighting measurements and testing; LEDS and plant lighting

(continued)

Table 1. (Continued)

Research team leaders	Title and responsibility	Name of research team and school	Research team topics
Jorma Kyyrä	Head of the Department of Electrical Engineering and Automation, Professor and Research Team Leader	Industrial and Power Electronics, School of Electrical Engineering	Novel computational schemes and intelligent systems; electrical power/energy engineering; modelling hybrid-powered utility vehicles and their power converter and energy-storage units; energy-efficient (or 'green') data centres; energy-efficient townhouse
Pirjo Kääriäinen	Professor and Research Team Leader	CHEMARTS, School of Chemical Engineering and School of Arts, Design and Architecture	Performance and design of advanced cellulosic materials; design-driven technology development processes; future business seeds of sustainable world of materials; biomaterials; plant-based materials
Harri Lipsanen	Professor and Research Team Leader	Nanoscience and Advanced Materials, School of Electrical Engineering	Nanomaterials; nanostructures; and advanced materials for nanoelectronics and nanophononics; graphene and related two-dimensional materials; energy efficiency especially in advanced LED and solar cell concepts; nanofabrication by atomic layer deposition; micro-, nano-, and optoelectronic devices based on semiconductors (GaN, GaAs, InP, Si) and their nanostructures (such as quantum dots, nanowires, and black silicon)
Mari Lundstrom	Professor and Research Team Leader	Hydrometallurgy and Corrosion, School of Chemical Engineering	Hydrometallurgical processing of primary and secondary raw materials; electrochemistry; secondary raw materials for the development of new processes and materials in circular economy of metals; sustainable industrial-scale process development
Jukka Manner	Professor and Research Team Leader	Internet Technologies, School of Electrical Engineering	Green ICT; evolution of routed ethernet and software defined; networking; cyber security; military and government communication infrastructures and protocols
Yrjö Neuvo	Research Director and Professor	Aalto Energy Platform and Energy Conversion, School of Engineering	Thermal materials and bioenergy conversion; thermodynamics; fluid mechanics and chemistry in energy technology; combustion and spray technology
Marko Nieminen	Professor and Research Team Leader	Digital Opportunities, School of Science	Services for sustainable business in emerging markets; low-barrier digital service platform for citizens living in informal communities
Antti Punkka	Professor in the Finnish Open Climate University Initiative	Systems Analysis Laboratory, School of Science	Mathematical theories and algorithms of optimization; control and decision-making to the practical interactive computer modelling and decision support systems and risk and technology assessment; complex energy, production, and environmental systems; biological modelling; systems intelligence and applied philosophy in human organizations
Riikka Puurunen	Professor and Research Team Leader	Catalysis, School of Chemical Engineering	Sustainable catalytic processes from renewable resources; preparation of solid heterogeneous catalysts, e.g., by atomic layer deposition; characterization of solid heterogeneous catalysts
Miina Rautiainen	Professor and Research Team Leader	Geoinformatics—Remote Sensing, School of Engineering	Methods for monitoring vegetation from space; measuring and modelling the spectral and structural properties of forests; remote sensing; spectroscopy; radiative transfer modelling; laser scanning; and forest and environmental sciences
Ahti Salo	Professor and Research Team Leader	Systems Analysis Laboratory, School of Science	Mathematical theories and algorithms of optimization; control and decision-making to the practical interactive computer modelling and decision support systems and risk and technology assessment; complex energy, production, and environmental systems; biological modelling; systems intelligence and applied philosophy in human organizations
Sanna Syri	Professor and Research Team Leader	Energy Efficiency and Systems, School of Engineering	Energy generation; energy consumption system; efficient energy use and indoor climate in buildings; societal and economic impact of energy technologies; transformations of energy systems to reach carbon-neutrality

of science outputs and authorization and participation in science production (Vicente-Saez et al. 2020). We defined the themes according to the research objectives. We used the qualitative data coding software tool Atlas.ti to assist in the process of coding and memo writing. Third, we organized all identified themes into significant clusters. We distinguished how the four theorized dimensions of openness in science (Vicente-Saez et al. 2020) were present and differed in significant ways in each research group. We also identified commonalities as well as distinctive features in the open science practices—open sharing and inviting practices—of research teams working on climate change issues. We further identified key challenges and efficiencies gained in opening up science that were encountered by the research teams We identified the impact of open science practices on the role of researchers when researching and developing actions, solutions, and technologies for sustainable development. Fourth, we developed our initial template based on the clusters of themes identified. Due to the diversity of the research disciplines and with the aim of achieving a comprehensive representation of the data, we decided to repeat steps 1, 2, and 3 by working systematically with a new subset of five interviews, one from each of the schools of Aalto. We met frequently as a research team to refine the template and include new themes, redefine existing themes, and delete themes. Fifth, we formulated and agreed on the final template. We applied the template to the entire data set. We then recoded previous interviews. This template was the basis for performing the final analysis of the coded data and structuring our findings. Finally, we prioritized the most relevant insights considering how and to what extent existing and recently adopted open science practices and the underlying principles of research teams at universities support the advancement and development of solutions for sustainable development. In the next section, we present our findings.

4. Findings

4.1 An expansive normative structure of open science in the digital era in sustainability

Through our study, we infer an expansive (i.e. marked by expansion) normative structure of open science, including a new set of open science practices, norms, and institutional goal among researchers working on sustainability at universities (see Fig. 1). This expansive normative structure is enabled by the active use of digital technologies and tools and open physical and digital infrastructures by research teams and their development of new scientific practices. Based on the analysis of our primary data (interviews), triangulated with our secondary data (policy documents, collected web-based material, and observations), we expose key characteristics and the operation of the new sets of norms and institutional goal for open science practice that the studied researchers embraced. The next section presents in detail our findings on the expansive normative elements of open science in the digital era in sustainability.

4.1.1 The expansive norms of open science

Open science norms are professional practices of proper or acceptable behaviour upheld by the values and mindsets of researchers. Among the 23 teams, we found that a majority, 19 research teams, were assigning to and embracing expansive

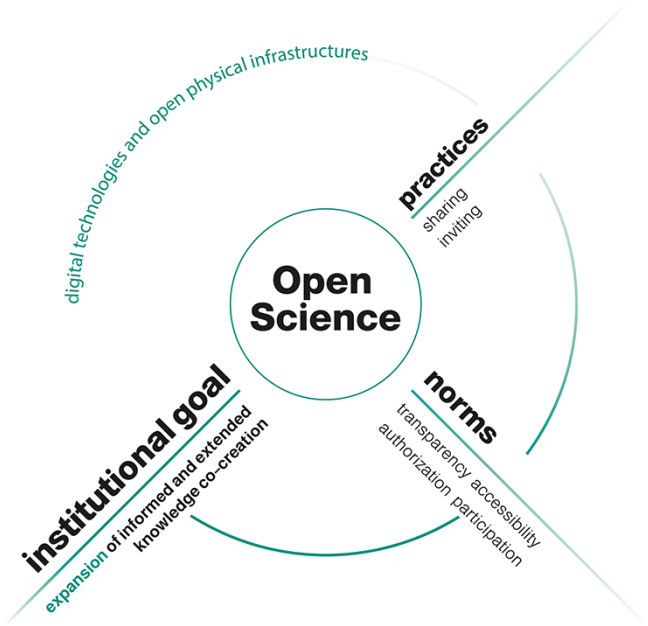

Figure 1. An expansive normative structure of open science in the digital era in sustainability.

openness norms The leaders of the research teams explained to us that solving grand challenges such as climate change has pushed them to actively explore and adopt novel open science practices.

We found that the research teams we interviewed had all embraced novel open science practices, both open sharing and open inviting practices (Vicente-Saez et al. 2020), in multiple forms and with diverse levels of openness. The various open science practices—*technical methods*—of the research teams we documented were founded on the open science principles of transparency of science outputs, accessibility of science outputs, authorization in science production, and participation in science production (Vicente-Saez et al. 2020). With the expansive use of open science practices in sustainability research, the questions that researchers are asking have also evolved. With constantly developing open science practices, scientists' underlying principles and norms of science are also evolving.

We distinguished a subset of expansive norms that address openness in the sharing of knowledge in open science in relation to the transparency and accessibility of science outputs. Transparency addresses what is shared in open science. This includes ideas, data, methods, and results that are shared in a transparent manner. A clarifying example of the expansive transparency norm in open science practice in research teams working on sustainability and climate change issues was given by Juanjo Galán, research team leader of the AaltoLand Group, who explained, 'When you're dealing with complex issues in which society is involved, you need to have a kind of high level of connection with the society, and sharing different stages of the research process is really important'. This involves 'the different stages of the research process, [including] the definition of the research problem, the definition of the research questions, and the applications of the methods'. We also found that the teams we studied embraced an expansive norm of accessibility. Accessibility addresses the question of with whom science is shared. We found that the research

teams we studied had increasingly engaged in broadening sets of local, national, regional, and global collaborative networks over the last 10 years. An illustrative example of how openness is ascertained by the accessibility of science outputs was given by Idil Gaziulusov, research team leader of the Sustainable Design Group (NODUS), who noted that 'everything that we produce, every scientific output that we produce, I think as long as there are resources, is open. I have recently published a book, and that's also open—I mean, it's hard copy is, of course, being sold, but we paid, Aalto has paid for making the electronic version openly accessible'. I: 'To everyone?' R: 'Everyone'.

We further distinguished a second subset of norms that address openness in the production of knowledge in open science: authorization and participation. Authorization addresses norms of openness with respect to how science is created and executed. We observed that the research of the teams we studied had changed from being conducted solely by the research team to being co-produced with stakeholders. This shift in creating and executing research highlights the ability to trust participants and to equally confer trust to receive valuable inputs into the science process. The norm of authorization in science production—instilling trust in consortia's communities and crowds invited to the scientific process—has gained a central role in sustainability research. A clarifying example of this expansive norm of authorization in science production, encompassing the expansion of trust-based principles, was given by Pirjo Kääriäinen, research team leader of the CHEMARTS Group: 'My research group is about societal transformation for sustainability, which means that we have to work with societal actors (…) So we do co-create knowledge, methods, outputs with knowledge users or non-academic as well as, of course, academic stakeholders'. We also found that the teams we studied adopted an expansive norm of participation. Participation addresses the question of where science is created. We found that among the teams we studied, science production in sustainability research has expanded to co-production with a wide set of geographical networks, ranging from local, national, and regional to global collaborative networks. An illustrative example of the expansive norm of participation in science production was given by Ahti Salo, research team leader of the Systems Analysis Laboratory Group: 'So the biggest [workshops] have had some 400 stakeholders from all over Europe […][the invitation] was sent to a group of selected stakeholders rather than everyone in the world. But – I mean, the platform was open then to all who were invited'.

4.1.2 The expansive institutional goal of open science

We found that the institutional goal of open science is expanding with regard to the norms of researchers and their teams and the new open science practices employed in sustainability research. In addition to the expansion of the norms of open science, based on our analysis of the 23 research teams, we identified an expansive institutional goal of open science, moving from the 'extension of certificated knowledge' (Merton 1973: 270) to one that is focused on informed and extended knowledge co-creation in the digital era.

This expansive institutional goal arises from the interrelationship between the expansive subsets of norms of open science discussed above as well as the expansive open science practices in sustainability research in the digital era. Sharing ideas, data, methods, and results with local, national, regional, and global collaborative networks of participants in research brings to the forefront informed knowledge co-creation. This is reflected in the comment provided by Sanna Siri, research team leader of the Energy Efficiency and Systems Group: 'Basic information on what is happening in the electricity systems, what is right now the electricity production mode in any European country, that's nowadays available—that's the other link that I'm sending to you. So we need either the raw data, the input data for our models, or we need the electricity system data for calibrating our models so that we can see what happens in reality, and we try to reproduce that with our own models. So those are extremely useful'. Trusting collaborative networks of participants in research in the form of consortia, communities, and crowds at the local, national, regional, or global level invited to science production is a key normative element in science that contributes to extended knowledge co-creation. This idea was highlighted by Antti Ahvala, Associate Vice-President for Campus Development and research team leader of Group X: 'We have had workshops. Not only with all possible authorities and representants from the university, like the education side, but also from real estate, and then the actual schoolchildren and teachers, people from the management of the school. So that…the co-creation, co-designing processes are more inclusive'. Therefore, we synthesized an expansive institutional goal of open science in the digital era, which was observed in our study among research groups working on sustainability and climate change issues, as the expansion of informed and extended knowledge co-creation.

4.2 Open data practice transforming research processes in sustainability

We found that open data practice is the major open sharing practice adopted by research teams when combating climate change and its impacts. Open data have radically transformed university research teams' processes of collecting, evaluating, and circulating data and designing and performing scientific studies in the field of sustainability. First, we found that open data access and use (inbound) has become a cornerstone practice of the research process in sustainability. Second, we observed that data sharing (outbound) has enabled responsible, inclusive, and sustainable research when combating climate change and its impacts and has increased the dissemination of raw data within academia and society. Third, we found that many of the university research teams reported efficiencies gained from working with open data. When compiling open data (inbound), research teams have accelerated, reduced the cost, and increased the relevance of their research. By sharing their data (outbound), research teams have guaranteed the future accessibility and usability of their work. We found that data sharing is becoming a central inducing mechanism for knowledge transfer in the digital era. Finally, we identified the challenge of quality assurance demands for open data (inbound) and the challenge of opening up sensitive data sets (outbound), especially with qualitative data, when researching in the field of sustainability.

4.2.1 Open data as knowledge creation (inbound) and circulation (outbound) practice

We found that open data access and use by research teams have enhanced researchers' possibilities for theoretical modelling, performing analysis, testing solutions, and enabling policy recommendations with better generalization and accuracy of dynamic phenomena. Researchers have developed complex and data-rich models for supporting climate change mitigation actions and policies. Ahti Salo, research team leader of the System Analysis Laboratory Group, explained how they 'have contributed to the International Panel on Climate Change reports (…) Tommi Ekholm, he developed the studies for the Finnish scenarios for 2100, supporting the climate change target, emissions targets for Finland in 2100 (…), and much of the data would come from public sources'. We found that knowledge creation in sustainability has been led by compiling data from public, reliable and trusted data sets from international organizations (e.g. the United Nations), national governments (e.g. Finland's government), and public bodies (e.g. the Finnish Environment Institute). Harri Koivusalo, research team leader of the Water and Environmental Engineering Group, explained how their research is open-data driven, especially when working with natural water resources issues from the context of scarcity of resources: 'This research is very much based on open data […] data resources that are there are from United Nations […] data from the Finnish meteorological institute are open source, and […] when we are working with water resources, we are interested in the weather conditions, in the meteorology, with the climate sense projects, and so we very much rely on these open data'. Open data access and use have allowed researchers to participate in the research process of global sustainable solutions by obtaining access to distant resources of knowledge. Harri continued, 'They are working with developing countries, and their research very much relies on all sorts of open, large-scale data projects'.

We found that data sharing has become a rooted practice in the field of sustainability to increase the internal (academia) and external (society) accuracy, transparency, credibility, reliability and usability of data. Marketta Kyttä, research team leader of the Spatial Planning and Transportation Engineering Group, described how this process is being undertaken by her research team: 'We are now going to, in the future, always publish our datasets in that (open) repository that we will select (…) we refer to those openly accessible datasets for, you know, if anybody wants to do further research or check our analysis'. Data sharing is considered a movement from the paradigm of the dissemination of research results—a separate phase of the research process—to the circulation of knowledge—a new phase of the research process. We identified research teams' intrinsic and extrinsic motivators for knowledge circulation. First, we identified inclusiveness as the intrinsic motivator. Researchers have opened up their data sets not only to advance science according to its ethos but also to democratize and allow worldwide research participation in science. Miina Rautiainen, research team leader of the Geoinformatics—Remote Sensing Group, explained, 'Some team members come from developing countries, and they have a very strong personal sense of duty'. Second, we identified career development as an extrinsic motivator. Researchers have shared their own data sets for other researchers to use and cite their studies, to increase the visibility of the research group, to promote their skills in collecting data, and to find new public and private collaborations. Miina noted, 'It can be a motivation to get more citations of their own papers and to promote their own career'.

4.2.2 Efficiencies in the research process from open data

We found that open data (inbound) practice has accelerated the research process in sustainability and reduced its cost. We also found that research has increased its relevance by supporting policy development processes. Scenario modelling and analysis has become quicker and is built on comprehensive, realistic, larger, and longer-term data sets. Sanna Syri, research team leader of the Energy Efficiency and Systems Group, explained the impact and value of this practice in her research team: 'It helps, tremendously, our work, all of this input data or comparison data freely and quickly available. So it speeds up our work; we can more easily develop our own scenarios of any systems that might be helpful, might be climate friendly, carbon-neutral'. Researchers can gather, organize, interpret, and combine data from different private and public sources more efficiently and competitively. Minna Rautiainen, research team leader of the Geoinformatics—Remote Sensing Group, explained that 'open data has been a big thing (…) now we can get forty years' time series of satellite data for the whole planet for free'. Furthermore, we found that open data (outbound) practices are making the knowledge transfer mechanisms at universities evolve. Researchers are increasingly sharing their raw data sets to ensure the future accessibility and usability of their data for research and innovation purposes. One reason for this is that researchers may change their workplace, and they want to have full access after relocation to the data they gathered or produced. Riikka Puurunnen, research team leader of the Catalysis Group, highlighted this mechanism: 'It's really an issue that what you did in the previous place stays there. And if you publish it openly, well, you always can access it yourself'. Additionally, researchers are opening up their data sets in sustainability research to provide societal, environmental, economic, and cultural value. Kamyar Hasanzadeh, coordinator of the open data initiative in the Spatial Planning and Transportation Engineering Group, explained that everyone (citizens, researchers, firms, or municipalities) can access their data for education, research, and innovation purposes: 'Yes, the license we have used is quite flexible. There are no restrictions'.

4.2.3 Open data challenges in the research process

We identified the challenge of quality assurance demands for open data when compiling these data for research in sustainability. The accessibility of open data has not immediately brought trust. Researchers have been required to develop new skills, tools, and support services to verify the robustness, applicability, and reliability of all data openly available on the web. As Harri Lipsanen, research team leader of the Nanoscience and Advanced Materials Group, expressed to us, 'You need an expert to really find out what is the truth, what is really relevant'. We also found that researchers have encountered challenges when sharing open data to enable sustainability research, such as the challenge of anonymizing data and maintaining the quality of data with regard to opening up sensitive data sets, especially for qualitative data. Making

data available has made it difficult to promptly confer transparency. Researchers have been required to develop new skills and tailor-made protocols and infrastructures to share their research data fairly and ethically in line with GDPR regulations. Idil Gaziulusoy, research team leader of the NODUS Group, noted, 'Anyone who is doing qualitative research and who is doing research with humans knows that you need to consider the privacy of data, personal data; you need to consider whether that person is ok with being quoted openly or not'.

4.3 Transdisciplinary research practice transforming research processes in sustainability

We found that transdisciplinary research practice is a major open inviting practice adopted by research teams when combating climate change and its impacts. Transdisciplinary research practice has become a pioneering practice that drives the societal agenda in the field of sustainability. First, we found that transdisciplinary research practices by research teams have enlarged their research processes in terms of academic and societal engagement and collaboration by recognizing and including new participants in very early research phases. Second, we found that many of the university research teams reported efficiencies gained from working with transdisciplinary research. Transdisciplinary research practices have promoted more targeted science outputs and strengthened knowledge recombination when combating climate change. Finally, we identified the challenges of the silo discipline mindset and current reward systems when adopting transdisciplinary research practice in the sustainability field.

4.3.1 Transdisciplinary research as knowledge recombination practice

We found that transdisciplinary research practice by research teams has boosted knowledge recombination—the agile creation and circulation of ideas, data, methods, and results—by authorizing new participants in several phases of the research process in science production. As Idil Gaziulusoy, transdisciplinary research team leader of NODUS Group, explained, 'We do see everyone as an expert, and we use the terms academic expert, non-academic expert, because everyone is an expert in something'. We distinguished three dimensions of transdisciplinary research at universities. The first is academic transdisciplinarity, in which researchers from different research disciplines recombine their knowledge. Marjo Kauppinen, research team leader of the PREAGO Group, explained the value of a recent collaboration between the School of Science and the School of Arts, Design and Architecture: 'Having people from arts and design, it can make our research much more interesting, and it can create something special. So, they have a bit different research methods (…) they're now combining their research knowledge with our research knowledge'. The second dimension of transdisciplinarity, citizen science, focuses on researchers who engage with citizens to combine their knowledge. Researchers have not only gathered data from/through citizens; researchers have also authorized citizens in science production by engaging them in new research phases. Citizen science practices have evolved. A clarifying example of this new kind of citizen engagement was given by Marketa Kyttä, research team leader of the Spatial Planning and Transportation Engineering Group, who explained, 'It's a little bit problematic to co-analyse these datasets, but we have done that sometimes, for example, in this Helsinki City Masterplan project (..) there were some focus group events organized with the idea that groups of people would help us deepening the data'. The third dimension of transdisciplinarity, professional transdisciplinarity, involves researchers who combine knowledge with different professionals of public and private organizations (companies, municipalities, NGOs, states, or international organizations), with the aim of having a better understanding of the state of the art and anticipating possible futures and alternatives when combating climate change. Antti Ahvala, Associate Vice-President for Campus Development and research team leader of Group X, provided an illustrative example of how to set up this practice among different academics, professionals, and students: 'So we have built a Lego model of the campus (…) So if you made changes in the Lego model, it shows changes in biodiversity, CO2 emissions, innovation capacity, and those kinds of things. But it's very important that the interface is user-friendly and open because anybody can play with Lego blocks. And they don't have to know anything about it (…) It's also good that it's an attraction for people to gather there, and we can play with politicians and city officials'. We found that these three dimensions were combined according to the nature of the research topic and the expertise required of the participants. Transdisciplinary research practice has become a holistic open science practice that does not use only one open science practice but rather combines several, including action research, co-creation platforms, crowdsource practices, interdisciplinary research practice, open physical labs, and participatory design. Pirjo Kääriäinen, research team leader of the CHEMARTS Group, provided an open-minded perspective on this: 'You have these open labs […] BioGarage was just opened last week in a design factory now by four of us for some genetic engineering stuff. So of course that's one way to try to take more and more people to get them involved this bio art; there are different kinds of labs and hubs and so on where anybody basically is supposed to be able to come and work, hack things and so on'. In summary, knowledge recombination by transdisciplinary research practice allows multiple science disciplines to explore new knowledge avenues in the field of sustainability.

4.3.2 Efficiencies in the research process from transdisciplinary research practice

We found that university research teams working with transdisciplinary research practices have gained efficiency. Transdisciplinary research practices have promoted more targeted science outputs when combating climate change. Researchers have obtained ideas, data, methods, and results that better take into account societal needs by recognizing, including, and integrating scientific, professional, and citizen knowledge from the conceptualization phase of research. Juanjo Galán, research team leader of the AaltoLand Group, highlighted these efficiencies: 'In climate change, we are talking about how communities can get engaged in climate change adaptation; basically, we need to know what the needs of those communities are and how they can participate. We don't want to give them a ready product; they are part of the process'. We further found that the constant interaction between researchers and participants through

transdisciplinary research practices has strengthened knowledge recombination. As Mark Hughes, research team leader of the Wood Material Technology Group, explained, 'I suppose that's the most structured form of co-creation that I've experienced. Yeah, that's been very beneficial, because then you've got clear outputs from the time you spent together'.

4.3.3 Transdisciplinary research practice challenges

We found that the silo discipline mindset has inhibited transdisciplinary research practices. Yrjö Neuvo, Research Director in Energy Conversion and Aalto Energy Platform, shared this concern and discussed how new singular transdisciplinary research platforms have tried to overcome it by promoting cross-fertilization among participants in research: 'Silo thinking is a really big risk. And there are so many different truths, so one really has to have breadth and curiosity. I think that in the platform (…), we have broad understanding, we can organize innovative events'. He continued, 'Transdisciplinary all the time—that has been kind of my guiding principle over the years'. We also found that traditional research incentives—reward systems—have inhibited the adoption of transdisciplinary research practices by research teams. Pirjo Kääriäinen, research team leader of the CHEMARTS group, provided an illustrative example of this concern: 'If we want to do something, we need to have two articles, for example, one that will be for the scientific and technical community and the other for the design community. It's quite interesting and it's one of the problems…it's been recognized and we really also try to tackle'.

4.4 A new academic entrepreneurial ethos transforming research and innovation in sustainability

In addition to changes in the open science practices and norms among researchers in the field of sustainability and climate change, our study reveals how researchers are increasingly becoming entrepreneurial in their work. Of the 23 team leaders we interviewed, 15 had gone beyond existing ways of doing research by being innovative and entrepreneurial in setting up knowledge co-creation activities and being explorative in knowledge value creation, circulation, and recombination work. In their efforts, we found that the boundaries between research and innovation are increasingly diffuse. It is difficult to separate where research ends and where innovation begins, as also noted by our informants in the earlier sections. We found that research and innovation intertwine and are happening at the same time, especially among university research teams who attest to expansive openness in sustainability research. It is this expansive openness that causes open science and open innovation to take place at the same time. We next present a synthesis of our findings regarding what we consider a new type of academic entrepreneurial ethos that encompasses three distinguishing characteristics of moral nature and guiding beliefs that drive research and innovation in sustainability at universities: (1) the adoption of expansive norms of open science; (2) a mindset of radical creativity, a sense of initiative, and passion for exploring new innovative solutions; and (3) the promotion of responsibility and inclusiveness as key values.

Through our in-depth analysis of 23 research groups, we found that the development of global actions, solutions, and technologies for combating climate change through open science and innovation practices was led by a new type of academic entrepreneur. All of the research groups embraced the expansive norms of open science in their development of global actions, solutions, and technologies for combating climate change. Riikka Puurunnen, research team leader of the Catalysis Group, provided a good example of this expansive norm of open science as part of her academic entrepreneurship: 'I'm openly discussing things, for example, on Twitter: work-related things, research-related things, funding-related things, problematic terminology, all kinds of things'. In our studied research teams, we found individuals who embraced a new kind of academic entrepreneurial mindset built on radical creativity, a sense of initiative, and a passion for exploring new, innovative solutions. Yrjö Neuvo, Research Director in Energy Conversion and Aalto Energy Platform, explained this mindset: 'First of all, it means curiosity. Desire to learn and discuss. Also, it's not being too formal, too strict. You have to accept different ways of thinking and different attitudes and policies … mental flexibility is a pretty good term for that'. Finally, we found that the research leaders and researchers working on climate change in the teams we studied promoted responsibility and inclusiveness as key values as part of their academic entrepreneurship. A comment by Marko Nieminen, research team leader of the Digital Opportunities Group, captures the essence of these values: 'If we are developing some new services that we hope are somehow having some societal impact, we need to have the possibility to include the citizens, people who are being influenced by those, let's say, future services that we are studying, somehow, in the early stages'. He continued, 'It cannot be done only by the developers, only by the designers, only by the researchers; you must include the viewpoints arising from the context that you aim to affect somehow or understand in your research or affect through your designs'.

This new academic entrepreneurial ethos is changing the role of researchers who are researching and developing innovative solutions for combating climate change in the field of sustainability. Researchers have developed new actions, solutions, and technologies beyond the traditional conventions for organizing and managing research and innovation at universities. A statement from Mark Hughes, research team leader of the Wood Material Technology Group, reflects this idea: 'I think the boundary between research and innovation is a little bit more blurred, at least in my mind now. I'm not quite sure what we do, whether we are doing innovation or whether we're doing research half the time; it's a little bit of both, I think'. The role of researchers is currently evolving from lab-desk science management towards platform-community science management, from 'pure scientist' (Saarela 2019) to academic entrepreneurs. Researchers are simultaneously learning, researching, and innovating together with a wide set of participants to achieve a sustainable world. Their activities exceed what is currently promoted, recognized, and rewarded through the existing research, innovation, and knowledge transfer mechanisms at universities. Researchers are becoming active explorers of knowledge, solutions, and processes to solve societal challenges. We assert that this new academic entrepreneurial ethos is expanding the role of researchers in the digital era and, with it, the traditional process of knowledge value creation and transfer at universities.

5. Discussion

Our study makes a major theoretical contribution by advancing the understanding of the social structure of the open science institution in the digital era.

First, we update the responsible, social, and sustainable goal—an expansive institutional goal—of open science. The 'institutional goal' of open science as synthesized by Merton is the 'extension of certificated knowledge' (Merton 1973: 270). Based on our findings, we suggest that the goal of open science in the digital era has evolved to encompass *the expansion of informed and extended knowledge co-creation*. Recognizing this updated institutional goal is key for understanding, defining, and managing the research process in the digital era.

Second, we identify a new set of expansive norms underpinned by the transparency and accessibility to science outputs and authorization and participation in science production. We find that the 'institutional imperatives' (Merton 1973: 270) of open science in the digital era, the new set of expansive norms of open science, build on Mertonian norms of communalism, universalism, disinterestedness, and organized scepticism but expand the ethos in science in terms of cooperation between collaborative networks of participants in research: researchers, universities, research institutes, companies, NGOs, states, municipalities, citizens, and international organizations.

Third, we show how open data (inbound and outbound) and transdisciplinary research practices, 'technical methods' (Merton, 1942 in Merton 1973: 270), the new expansive open science practices in the digital era, are radically transforming the traditional knowledge creation process—the research process. We propose that the new research process in sustainability research with these new open science practices seeks out informed and extended knowledge co-creation through knowledge creation, circulation, and recombination by including collaborative networks of participants in research from the very early conceptualization and design to the following research stages.

As such, our findings contribute to the academic foundations of the philosophy, sociology, and economics of science in the evolving digital era. We infer an expansive normative structure of open science among researchers working on sustainability that is key for designing and fostering efficient science policies in the evolving digital era. This new expansive normative structure of open science enables a 'change of paradigm' (Kuhn 1970) with regard to the previous modern or open science institution era. The new practices, norms, and institutional goal of open science trigger a new paradigm for co-creating scientific knowledge in the digital era. By informing and extending the research process to more collaborative networks of participants, including scientific, professional, and amateur users of scientific knowledge, science disciplines—theories—are evolving. Researchers are recombining ideas, gathering new data, adapting new methods, and using new results from other disciplines and other participants in the sharing and production of science outputs for sustainable development. Our conceptual model of the expansive normative structure helps researchers identify and articulate what we call a second open paradigm in open science's social institution, which occurs in the ongoing evolving digital era in our society today.

Finally, our study makes a contribution by identifying a new entrepreneurial ethos with distinct norms, mindset, and values in academia related to the simultaneous efforts to research and innovate solutions to advance sustainability and combat climate change. This new academic entrepreneurial ethos advances the role of researchers at universities (Perkmann et al. 2013) in the evolving digital era from lab-desk science management towards platform-community science management, from pure scientists (Saarela 2019) to academic entrepreneurs.

The expansive normative structure of open science in the digital era and the new academic entrepreneurial ethos are expanding the second and third missions of universities. First, the new normative structure is transforming universities' traditional organizational structure of science basic research, applied research, and experimental development (OECD 2015). Open science's new practices, norms, and goals are expanding research fields' openness and, with it, the standard boundaries between research disciplines. We find initial evidence of how the overall openness of a research field varies in relation to the involvement of participants in the research field and the maturity of the research field. Expansive openness in science goes beyond the traditional borders of conventions of organizing science disciplines and is reflected and extended in a multitude of arenas of knowledge development, including basic research, applied research, humanities, experimental development, design, and art. Second, the new academic entrepreneurial ethos is evolving the traditional rewards systems for scientists and knowledge transfer mechanisms At the centre of this new ethos is our study's observation that openness in science can become an impactful incentive and mechanism for the creation of actions, solutions, and technologies that simultaneously address cultural, economic, environmental, societal, and technological values. Open science practices achieve knowledge and technology transfer from the first steps of the research process by including participants in the informed and extended knowledge co-creation process.

The new academic entrepreneurial ethos can be considered itself an institutional model for universities working on sustainable development in the digital era. Past research on academic entrepreneurship has dominantly focused on researchers' commercialization activities (i.e. Braunerhjelm 2007; Walsh and Huang 2014) as well as their teaching and mentoring in entrepreneurship (Siegel and Wright 2015), although progress in widening academic entrepreneurship's definition has been promoted (Abreu and Grinevich 2013). Our findings expose how academic entrepreneurship has evolved to encompass professionals who act as enablers of institutional change (Suddaby and Viale 2011) in society and in the public and private sectors. As academic entrepreneurs, professionals in the university, i.e. researchers and university managers, are increasingly acting as institutional change agents by developing, testing, and adopting new practices, norms, and cultural-cognitive models (Scott 2008). Such institutional change activities include spearheading and promoting new standards, new practices, and cognitive norms of research within their social structures, including the university and the scientific fields in which they work in. The key values embraced by academic entrepreneurs—the expansive norms

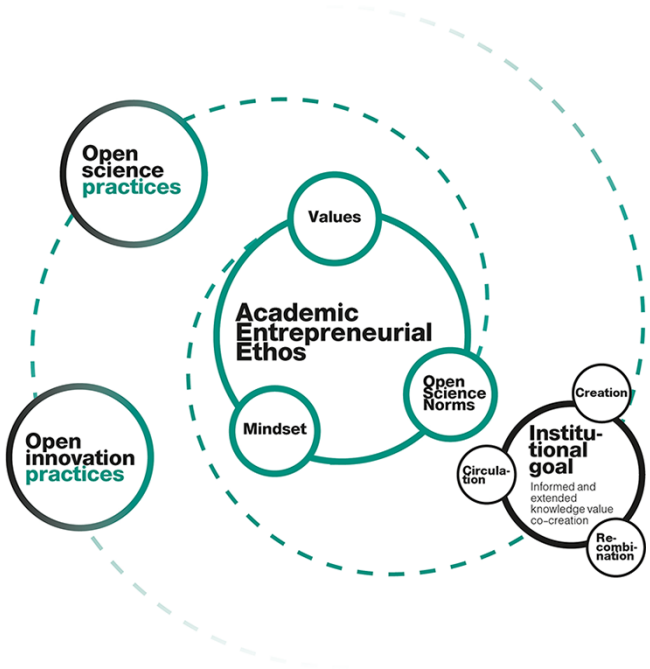

Figure 2. Open exploration: an expansive model of university research and innovation in the digital era.

of open science, the mindset of radical creativity, the sense of initiative and passion for exploring new innovative solutions, and the promotion of responsibility and inclusiveness—can be viewed as the university model's core parts in the digital era.

Based on our findings, we propose an expansive model (see Fig. 2) of university research and innovation led by entrepreneurial academics to guide the renewal of university governance in the digital era. This model can drive institutional change at universities. The new open science practices are expanding the ethos not only in science but also in innovation at universities. These new practices and the new entrepreneurial ethos by academics are transforming the established knowledge value creation and transfer process—the innovation process—in the digital era. We find that researchers have adopted open science and innovation practices with the aim of promoting informed and extended knowledge value co-creation, including knowledge value creation, circulation, and recombination, among multiple participants in research (e.g. researchers, universities, research institutes, companies, NGOs, states, municipalities, citizens, and international organizations) and multiple types of value (e.g. cultural, ecological, economic, technological, societal, or a hybrid combination of the five). We call this process in which entrepreneurial academics are engaged 'open exploration', which encompasses informed and extended knowledge value co-creation through open science and innovation practices. Open exploration is a new holistic research and innovation process at universities for advancing knowledge and developing actions, solutions, and technologies to achieve sustainable development.

Our findings have been inferred from an empirical study of research teams working within the sustainability field at one university. Like any university, this specific university is part of a society that promotes and encourages the philosophical principle of openness to guide and support the progress of society through reason and knowledge. Future research should therefore explore how the expansive normative elements—practices, norms, and institutional goal—of open science in the digital era operate in other research teams, in other research areas, in other universities, and in different national and international contexts. This will aid the measurement of the impact and efficacy of the normative elements of open science in the digital era. Furthermore, future research could also focus on how particular digital technologies and tools and/or open physical and digital infrastructures specifically expand these normative elements in specific research fields.

Our study provides several policy implications for university leaders and science and innovation policymakers. First, our study provides a solid understanding of the goal, norms, and practices of open science and their responsible, societal, and sustainable value as well as the efficiencies gained. These insights are central when designing effective university science and innovation public policies that promote the achievement of the Sustainable Development Goals established by the United Nations. Second, the proposed new open exploration model for research and innovation requires that universities rethink their second mission—research—and their third mission–knowledge and technology transfer—in the evolving digital era. Universities, as the main public infrastructure for open science and innovation, need to update the way that research and innovation are administered, organized, and managed. Universities, therefore, need to renew existing governance models and mechanisms to incorporate the expansive model for research and innovation in the digital era. Such governance mechanisms include research agendas, science reward systems, talent management systems, knowledge transfer mechanisms, and socio-economic interactions with the ecosystem and public engagement. In essence, our findings provide novel insights and important directions on how to advance an open exploration policy for holistic and public scientific knowledge co-creation and transfer at universities to address societal grand challenges, promote well-being for all, and boost a sustainable economy, society, and environment–in sum, for a sustainable world.

Supplementary data

Supplementary data is available at *SCIPOL* online.

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