Equitable Research Capacity Towards the Sustainable Development Goals: The Case for Open Science Hardware

Julieta Arancio[1,2], Mayra Morales Tirado[3], Joshua M. Pearce[4]
[1]Center for Science, Technology and Society, Drexel University, PA, US
[2]Centro de Investigaciones para la Transformación, Universidad Nacional de San Martín, Buenos Aires, Argentina
[3]Manchester Institute of Innovation Research, University of Manchester, UK
[4]Department of Electrical & Computer Engineering & Ivey Business School, Western University, London ON, Canada
https://doi.org/10.38126/JSPG210202
Corresponding author: jca88@drexel.edu
Keywords: open hardware; open science; open science hardware; research capacity strengthening; capacity building; global south; knowledge equity

Executive Summary: Changes in science funders' mandates have resulted in advances in open access to data, software, and publications. Research capacity, however, is still unequally distributed worldwide, hindering the impact of these efforts. We argue that to achieve the Sustainable Development Goals (SDGs), open science policies must shift focus from products to processes and infrastructure, including access to open source scientific equipment. This article discusses how conventional, black box, proprietary approaches to science hardware reinforce inequalities in science and slow down innovation everywhere, while also representing a threat to research capacity strengthening efforts. We offer science funders three policy recommendations to promote open science hardware for research capacity strengthening: a) incorporating open hardware into existing open science mandates, b) incentivizing demand through technology transfer and procurement mechanisms, c) promoting the adoption of open hardware in national and regional service centers. We expect this agenda to foster capacity building towards enabling the more equitable and efficient science needed to achieve the SDGs.

I. Introduction

Science funders, including government agencies, philanthropic organizations, universities, private funders, and multilateral organizations, play a key role in making science more efficient and equitable. Changes in funders' mandates (Else 2021; OSTP 2022) now demand sponsored researchers to practice open science, turning it into the new paradigm for science, technology and innovation worldwide (NASE 2018; UNESCO 2021). The potential for open science to drive transformation is still limited, however, as research capacity is unequally distributed. While 92% of articles address interventions in low and middle-income countries (LMICs), only 35% of authors in global health are from and work within LMICs (Iyer 2018). Beyond North-South dynamics, in high-income countries, other research capacity asymmetries exist between rural and metropolitan areas (Moran et al. 2019) or historically black colleges and universities (HBCUs) and non-HBCUs (Williams and Davis 2019).

Shifting policy focus from research products to processes can contribute to addressing some of these asymmetries. The crucial role of open, equitable, and sustainable knowledge infrastructures is widely discussed in open science (Budroni, Claude-Burgelman, and Schouppe 2019; Ross-Hellauer et al. 2022). Infrastructure discussions, however, tend to focus on the digital (Ferrari et al. 2018, Aspesi and Brand 2020, Carver et al. 2018). We bring attention to the overlooked role that science hardware plays as an inseparable component of research infrastructure. The software, data, and publications to be opened are supported by a layer of hardware that determines which data can be produced and who can produce it. This article discusses how the dominant hardware paradigm is a threat to research capacity strengthening (RCS) efforts in the Global South, while slowing innovation and scientific discovery globally. We then present policy options to promote an open hardware paradigm that can accelerate attaining the SDGs. We argue that conventional, closed-source approaches to science hardware make science inefficient and reinforce knowledge production inequalities by hindering access to appropriate, sustainable equipment in LMICs and least developed countries (LDCs).

The conventional approach to scientific equipment today is based on black box hardware, meaning devices for which design information is proprietary and therefore cannot be studied, inspected, or customized. Open science hardware, an emerging alternative paradigm, is a young phenomenon (Pearce 2018) and can refer to technology, a movement or a discipline (Arancio 2021). In this article "open science hardware" (OSH) is defined as: "any piece of hardware used for scientific investigations that can be obtained, assembled, used, studied, modified, shared, and sold by anyone" (GOSH 2016). It comprises standard lab equipment as well as auxiliary materials, such as sensors, biological reagents, and analogue and digital electronic components. With "research capacity strengthening" (RCS) we refer to the process by which individuals, organizations and societies develop abilities (individually and collectively) to perform functions effectively, efficiently and in a sustainable manner to define problems, set objectives and priorities, build sustainable institutions, and bring solutions to key national problems (GFHR 2004). We also use "distributed manufacturing" to refer to small, flexible, networked, geographically diverse, and scalable manufacturing units instead of long, linear supply chains, economies of scale and centralization tendencies (Srai et al. 2016).

II. Background: The challenges of research capacity strengthening

Donor governments, multilateral agencies and science funders design and implement RCS programs with LMIC countries to increase capacity in various research areas related to the SDGs, such as health research (Malekzadeh et al. 2020) and agricultural science (Schreiber et al. 2022). Approaches to RCS have evolved over time (Gadsby, 2011) from a top-down understanding of RCS as technology transfer in the 1980s, to a focus on developing individuals during the 1990s. Today, a more systemic, demand-driven approach considers RCS as the result of collaboration between multiple stakeholders, prioritizing local agency.

RCS programs often include investments in durable equipment; however, these do not necessarily translate into sustained capacity. For example, a study of research equipment at University of Zimbabwe identified that departments face shortage of spares, lack of maintenance expertise and funds, outdated equipment, and technology that manufacturers abroad are no longer able to support, with spare parts, in most cases, being exclusively imported (Nyemba et al. 2017). Ensuring sustainability of infrastructure is key, however funding policies often deem investments in research infrastructure as non-eligible expenditures, impeding infrastructure sustainability. The Special Program for Research and Training in Tropical Diseases, a significant initiative created in 1975 by international organizations to promote and conduct health research equitably, facilitated institutional acquisition of laboratory equipment for clinical research and diagnosis (Minja et al. 2011). Guidelines for investors highlight: "There is little point in refitting a laboratory with expensive and complex new equipment if there is no capacity in-country to service the equipment, unless the creation of the ancillary infrastructure is factored in" (ESSENCE 2014).

Sustainable access to useful research equipment became even more relevant during the COVID-19 pandemic. Conventional, centralized approaches to design and manufacturing failed to respond to the crisis in time, reinforcing inequities (Veselovská 2020; Chowdhury et al. 2021; Nikolopoulos et al.

2021) particularly for LMICs (Lewis and Martell 2021). Instead, the grassroots response that followed allowed communities to access necessary equipment with less dependence on global supply chains (Maia Chagas et al. 2020). These ad-hoc, open innovation ecosystems connected businesses, communities, universities, and government agencies to provide customized, locally produced equipment following a distributed manufacturing paradigm (Bowser et al. 2021). Production included personal protective equipment (Flanagan and Ballard 2020, Ballard et al. 2021, Skrzypczak et al. 2020, Nicholson et al. 2021, Hubbard and Pearce 2020), testing supplies (Gallup et al. 2020; Manoj et al. 2021, Abuzairi, et al. 2021a), sterilization equipment (Bentancor, et al. 2021; Santhosh & Yadav 2021), and electronics for ventilators (Pearce 2020a; Oberloier et al. 2022), among others. Governments coordinated these efforts to varying degrees of success. The *EUvsVirus* hackathon, organized by the European Commission, seized the advantages of open innovation by promoting interactions between civil society, innovators, partners, and investors to generate ideas for tackling COVID-19-related grand challenges (Bertello et al. 2022). In the U.S., several federal agencies formed the COVID 3D TRUST to compile, test, and evaluate 3D-printed PPE for clinical use, successfully identifying high-quality open-source designs (Bowser et al. 2020). Various UN agencies are currently facilitating policy discussions on seizing the potential of open hardware towards the advancing SDGs (UNCTAD 2021; Pearce 2022; UNESCO 2021).

In this context, for the first time, the 2021 UNESCO Open Science recommendation includes open hardware in an open science policy document. Open science hardware advocates have been working for the last decade on an alternative approach to hardware that fosters openness and collaboration (Pearce 2012; Gibney 2016; Arancio 2021; Stirling and Bowman 2021). Advances in software for hardware design (Medrano et al. 2017; Stirling et al. 2022) have made it possible to create, edit and share digital files for adapting and reproducing tools in numerous domains. Open licenses (Murillo et al. 2019) and standardization efforts (OSHWA 2010; Bonvoisin et al. 2020) improve documentation. Greater access to digital manufacturing (Al-Mashhadani et al. 2021) allows one to envision a distributed paradigm for science hardware, one that fosters local provision of research tools with less dependence on global production centers.

Two years after the start of the COVID-19 pandemic, there is an opportunity to accelerate the SDGs agenda by bridging open science policy with the distributed paradigm of open hardware innovation. The SDGs agenda demands increasing research capacity to quickly respond to global but highly situated challenges, while enabling equitable collaboration and interactions between multiple stakeholders. Open hardware is an opportunity for science funders to accelerate impactful research towards the SDGs in a transparent, collaborative, and inclusive way.

III. Science hardware today: Centralization, dependency, inefficiencies

Lack of access to science hardware can reinforce dependencies and systemic inequities in knowledge production in multiple dimensions. At a regional scale, although five African countries are in the top twenty contributors to marine plastic pollution, lack of access to analytical facilities results in only 3% of the research published being conducted in African contexts (Nel et al, 2021). In the U.S., funding allocation data show that even when the total federal R&D funding increases year after year, these funds remain concentrated in a relatively small number of institutions (NSF 2022). Funding allocation follows a pattern that rewards early success, increasing concentration of resources and research infrastructure in already well-funded teams and institutions (Bol et al. 2018). Outside academia, access to infrastructure for research is often poor. As with many other cases of community science around the world (Brown et al. 2016; Rey-Mazon et al. 2018), African American residents of Louisiana relied on do-it-yourself devices to monitor toxic chemicals in their ambient air, in a campaign against the Shell Chemical plant adjacent to their community (Ottinger 2010).

Due to their ubiquity, microscopes are a good case study for problems associated with proprietary hardware designs. The combination of microscopy and scanning methods in whole slide imaging (WSI) systems has recently been adopted as a standard in anatomic pathology (FDA 2017; Retamero et al. 2020). WSI devices produce digital images of tissue samples, generating data that aids doctors making diagnosis (McClintock et al. 2022) and can be used to train algorithms for automated detection (Business Wire 2020). The COVID-19 pandemic highlighted the importance of WSI systems due to their applications in remote education, teleconsultation, image analysis and primary diagnosis (Hanna et al. 2020; Mukhopadhyay et al. 2020; Liscia et al. 2020). Microscope manufacturers are concentrated in western Europe, the U.S. and Japan (Figure 1), with commercial digital WSI systems ranging from US$30,000 to US$250,000 only for hardware, a cost that has remained relatively stable during the last few decades (Patel et al. 2021). The hardware costs are increased when installing the same device in the Global South, because of import fees and duties, exchange rates and costs of transport/shipping along the supply chain (Bezuidenhout 2020; Pearce 2020b; Botero-Valencia et al. 2022). As budgets for R&D are already smaller in LMICs, these differences in costs result in even greater asymmetries in research capacity.

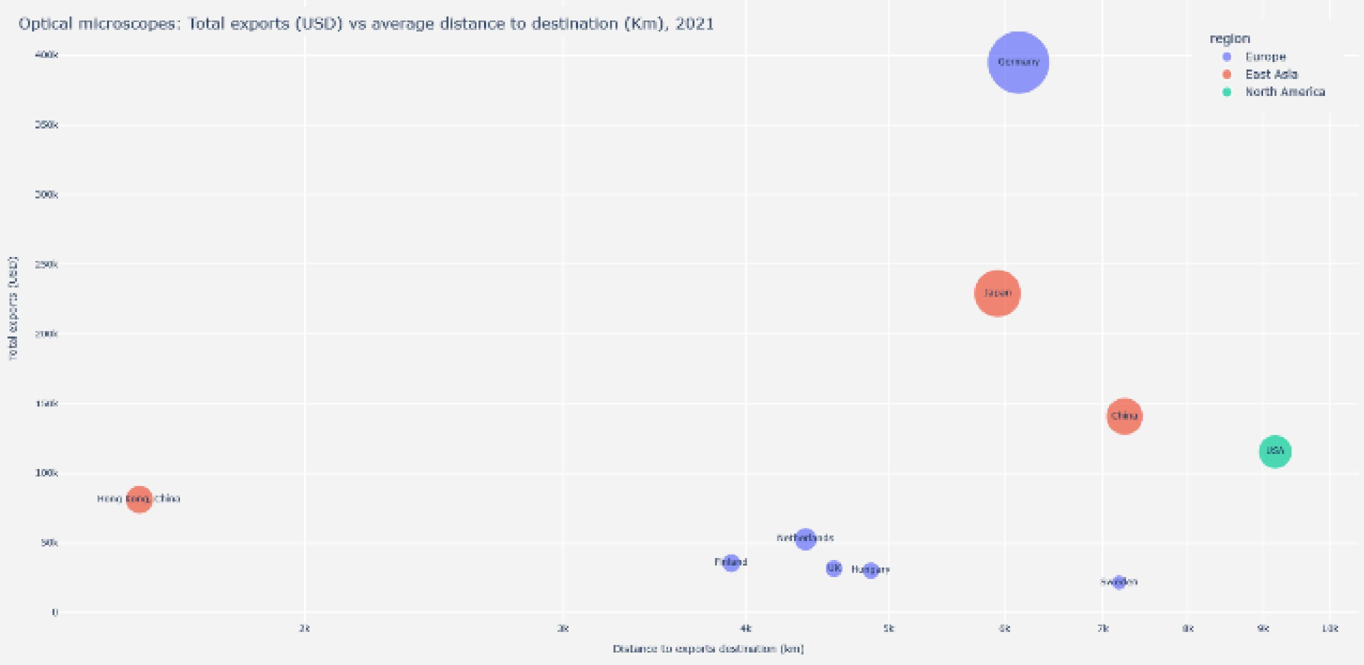

Figure 1. Exports value and distance to destination show optical microscope suppliers are concentrated in Europe, East Asia, and the US. Bubble size is proportional to country's share in world exports; average distance value corresponds to average distance between country and all partner countries weighted by corresponding trade values. (Data source: https://trademap.org, accessed July 2022; Author: J. Arancio; full size interactive chart available at https://thessaly.github.io/UNESCO-JSPG)

In addition to access to equipment, concentration of hardware manufacturing impacts the appropriateness of tools in countries that import hardware (Patnaik & Bhowmick 2019). As design activities are centralized and protected by intellectual property regimes, users working in contexts different from those of the design environment frequently find that tools do not work for their needs (Costanza-Chock 2020). Installing high-end research hardware demands access to stable internet connections, appropriate housing facilities and servers to store data (Ramoutar-Prieschl and Hachigonta 2020). Connectivity is a challenge for LDCs where internet infrastructure is still insufficient (ITU 2021). Moreover, equipment is often not designed for local environmental conditions and documentation is not available in local languages (Nyemba et al. 2021). When these constraints are not considered, hardware becomes obsolete by design in LMICs and LDCs (Maina et al. 2020).

Furthermore, sustainable research capacity is directly influenced by the ability to locally adapt, repair, and maintain hardware. Decades of North-South cooperation show that accessing equipment is relevant, but not enough for sustaining research capacity in LMICs (WHO 2021; COHRED 2008). Studies show that equipment is a constraint for research in Africa, and that dependency on foreign technical service is a main challenge (Oman and Lidholm 2002; Malkin and Keane 2010). Equipment donations are frequent, but sustainability of the equipment is threatened by lack of access to consumables and spare parts (Awuni and Essegbey 2014). An analysis of African research capacity on microplastics pollution shows that none of the equipment used for polymer identification, or their replaceable parts, are manufactured on the continent, making routine and mandatory maintenance difficult and cost intensive (Nel et al. 2021).

Finally, black box hardware prevents scientists from understanding how tools work, a requirement both for developing local maintenance capabilities and for ensuring researchers can conduct meaningful, situated science. Scientists have been identified as the users who modify their instruments the most, in response to their ever-changing research needs (von Hippel 1976). A recent study showed that scientific equipment suppliers introduce more new-to-the-market product innovations than do other firms belonging to the same sectors and with similar characteristics, and that university demand is particularly important for explaining these differences (Bianchini et al. 2019). The increased complexity of instruments (Carminati and Scandurra 2021), combined with black box designs and lack of interoperability (Hohlbein et al. 2022) result in experimental settings that are extremely difficult to inspect and customize. Today, lack of access to equipment information is a barrier to innovation and collaborative work; when possible, teams dedicate already scarce research time to reverse engineering devices.

IV. Enabling more and better research with open science hardware

Implementing open science policies for hardware access can be particularly useful to address the described capacity building challenges to meet the SDGs, particularly in the context of LMIC and LDCs (Maia Chagas 2018). Local manufacturing of open designs often results in more affordable products (Wittbrodt et al. 2013; Petersen and Pearce 2017; Pearce and Qian 2022). This trend is substantial with open scientific equipment generally costing less than 87% of proprietary equivalents (Pearce, 2020b). For example, syringe pumps are widely used for both scientific and medical applications, to deliver controlled doses of reagents in many laboratories. An open-source syringe pump which is locally built saves up to $2,500 anywhere it is fabricated (Wijnen et al. 2014). The designs for this open-source device have been downloaded over 10,000 times all over the world. Estimated savings reach millions of dollars when considering user downloads and substitution value, even when the cost of developing and sharing the design are considered (Pearce 2016). Being publicly available, local manufacturers can download open-source designs to build devices ranging from pipettes to complex polymerase chain reaction (PCR) machines, enabling research that was previously not feasible (Ravindran 2020).

Beyond access, open science hardware enables the adaptation of designs, a key feature of meaningful innovation. The Gorgas Project (Carrasco-Escobar et al. 2020), an initiative at Universidad Peruana Cayetano Heredia, illustrates the advantages of open science hardware in LMICs. The Project was led by two early career researchers (ECRs) studying how human mobility influences malaria transmission in indigenous Amazonian populations. The conventional methodological approach (Papworth et al. 2012) would have demanded dedicating most of the budget to importing a small number of proprietary devices. These devices, however, were not appropriate to the research context: they required connectivity features not available in the Peruvian Amazon, were made of materials that were not resistant to local weather conditions, and the user interface did not encourage adoption by research subjects (Arancio 2021). Thus, the research team developed a wearable device, drawing on a combination of open designs (Health Innovation Lab 2020). Using this approach, the team produced relevant, situated data that informed authorities about the relevance of human mobility for malaria transmission, leading to health policy changes at the national level (Arancio 2021).

In addition, access to open designs enables shorter supply chains (Collins et al. 2020). Access to microscopes, the gold-standard equipment for malaria diagnosis (WHO 2016), is limited in African countries where the disease is endemic (Maina et al. 2020). In 2015, Dr. Richard Bowman, an optics scientist, started the OpenFlexure project to design a 3-D-printed, research-grade microscope. In collaboration with a Tanzanian maker space, OpenFlexure microscopes are now produced locally and used by clinical researchers at the Ifakara Health Institute in Dar-es-Salaam (Knapper et al. 2021). OpenFlexure devices reduce the cost of access to high-resolution microscopy from more than US$20,000 to less than US$200 (Collins et al. 2020). As end-users are in close proximity, manufacturers can address problems with the equipment locally and incorporate improvements on demand (Stirling et al. 2020). The available microscopes have provided reliable data used by researchers to explore new methods including automated detection, and the manufacturer is in the process of medical certification in Tanzania (Bezuidenhout et al. 2022). Since 2015, OpenFlexure has grown into a global community of users and developers on every continent, including professional scientists, hobbyists, community scientists, clinical researchers, and teachers (Arancio and Dosemagen 2022).

Finally, producing actionable, local research towards achieving the SDGs demands new ideas and approaches to be tested (UN 2015; WHO 2021b; UNESCO 2021). Open science hardware enables new actors to participate in knowledge production, allowing neglected research questions to become visible (Arancio 2021). For example, a group of academics, family farmers, and activists in Argentina are using open hardware tools to set up an “open agroecology lab” (reGOSH 2022). Lab participants include academic researchers, rural extension workers, and social movements; they work on tools for soil health research, a line of inquiry that is overlooked by an official research agenda dominated by industrial agriculture. Co-designing the tools with farmers enables the community to learn about their practice while providing evidence to consumers in urban areas.

V. Making “open” the default in science instrumentation

The examples above illustrate how more equitable open science demands considering hardware infrastructure as a key component of RCS efforts. Despite the potential of open science hardware for accelerating more equitable innovation towards the SDGs, the field is still limited by a series of cultural, institutional, and technical challenges (Stirling and Bowman, 2021; Arancio 2021). Science funders, including governmental agencies, philanthropic organizations, universities and multilateral organizations, will play an important role in unlocking the potential of open science hardware (Heikkinen et al. 2020). We summarize these challenges and opportunities in the agenda below:

i. Incorporate open hardware strategies as part of open science policies

Open science mandates have effectively incentivized open practices in academia (Piwowar et al. 2018). Although open hardware in academia is directly linked with open science values and practices, these two communities are currently disconnected, making it difficult for institutions to justify support for open science hardware. To bridge this gap and foster open science hardware, science funders can incorporate open hardware as a recognized component of their open science mandates.

Incorporating open hardware as part of open science funders’ mandates for sponsored research would, first, provide a pathway for open hardware developers and maintainers in academia to legitimize their work. Second, it would connect open hardware practice with existing open science communities in academia, accelerating adoption. If funders ask grantees to provide the designs of hardware resulting from sponsored research, this will create an incentive for adoption of findable, accessible, interoperable, and reusable (FAIR) data protocols for building open hardware (Scheffler et al. 2022; Miljković et al. 2021).

Key stakeholders

Key stakeholders for this recommendation include funders supporting research for hardware development at universities and other research institutions, librarians and institutional champions providing support for open data and open access initiatives at universities, and researchers developing hardware prototypes as part of their daily work.

Advantages

The work of designers and maintainers of open hardware in academia, mostly ECRs, is not recognized under current evaluation schemes (GOSH 2018). This recommendation would provide a pathway for developers to make their work visible while allowing universities to track ongoing, unnoticed and potentially high-impact hardware prototypes. This impact could be easily tracked. Similar to Altmetrics (Garcia-Villar 2021), institutions can use several existing mechanisms in repositories that quantify downloads to track open hardware downloaded substitution value (Pearce 2015) without substantial effort, particularly when application programming interfaces (APIs) are available for the repositories.

Most universities maintain online repositories for researchers to publish open data and publications (Leonelli 2017). With little effort, these repositories could also host open designs and documentation. There is currently no comprehensive, vetted repository or database of open hardware designs. As recently proposed by the United Nations Conference on Trade and Development (UNCTAD 2021), a central database can make curated designs available, accelerating discovery and innovation across all sectors associated with the SDGs.

Disadvantages

Faculty members who are successful under current models of performance may resist any change in mandates or promotion processes, and administrators may fear additional new metrics to value faculty output. Moreover, asking researchers to publish open hardware designs demands training efforts for librarians and other focal points on best practices for open hardware.

ii. Incentivize demand for open hardware through funding and procurement mechanisms

A significant proportion of open hardware designs are developed in academia and remain in the prototype phase for long periods of time. There is a need for business partnerships to professionalize designs, supporting the process of meeting safety, technical and environmental standards. Science funders can support the uptake and professionalization of open designs by incorporating open hardware as a preference in procurement processes (Bizarro and Ferreiro 2022; Fisher 2013). Setting openness as another criteria for equipment purchase in sponsored research would lead to increased awareness and adoption of open science hardware. Technology transfer offices can further support business uptake of open hardware designs by including an “open pathway” in their science entrepreneurship programs.

Key stakeholders

Science funders who sponsor equipment purchase, procurement and technology transfer offices at universities and research institutions, and researchers using grant funding to purchase science hardware would be key to the implementation of this policy.

Advantages

There are already well-established open hardware business models (Pearce 2017) that allow firms to capture value using open designs by providing assembly, manufacturing, support, or consultancy services. The open hardware community has produced and maintains legal instruments such as open hardware licenses or certification programs, which can be easily adopted for evaluating vendors.

Disadvantages

Private enterprises that have benefited from past public funding of intellectual property (IP) that is then used for private profit may resist a push to place research in the public domain. Resistance is likely to be most substantial in countries with U.S.-style patent laws and from patent law firms. Furthermore, if purchase policy preferences are enacted, existing firms using conventional IP business models could be resistant to change due to the costs associated with overhauling their current IP system.

iii. Support the development of service centers based on open science hardware

Science funders, particularly public agencies, can tackle asymmetrical access to research equipment through the creation of national or regional service centers based on open hardware. These centers can maintain records on locally available research equipment, spare parts, and consumables, harmonizing documentation in local languages while maintaining a library of appropriate open science hardware designs and training local technicians. The centers can also function as a focal point for developing local suppliers of open hardware (Kauttu and Murillo 2017).

Key stakeholders
Science funders at the national and regional scale, existing research infrastructure facilities, laboratory technicians.

Advantages
The centers would allow researchers in LMICs to tackle some of the common challenges related to access to infrastructure, including dealing with import restrictions, problems with supply chains, and enabling appropriation of designs to local contexts. Science funders can support these activities by promoting the adoption of open hardware within existing research infrastructure centers. These centers often follow a self-sustaining model based on provision of consultancy, design, and training services for research institutions (Tsimidou et al. 2022).

Disadvantages
Incorporating open hardware into service centers demands training personnel and represents an ongoing operational cost that would be competing with other science funding programs.

VI. Consequences of inaction

The collaborative and inclusive approach of open science to research can alleviate some of the inefficiencies and inequities of our knowledge production systems. For this approach to become a transformative strategy, however, we need to urgently move from product-focused policies towards a process perspective that enables everyone to participate. Two years into the COVID-19 pandemic, the open hardware paradigm that enabled collaboration to save lives during the crisis can become instrumental for achieving the SDGs. Sustaining the current black box, proprietary model of innovation in science hardware means reproducing asymmetries in science and wasting valuable and scarce time and resources in reinventing solutions for urgent needs.

VII. Conclusions

Based on lessons from decades of international cooperation programs, we argue here that open science hardware as a paradigm presents opportunities for reducing asymmetries in research capacity worldwide. There is substantial evidence in the literature that open source accelerates innovation and reduces costs. When applied to scientific hardware, open source allows new actors to actively participate in research, enlarging and diversifying the pool of ideas and solutions necessary to achieve the SDGs. We proposed three concrete recommendations to bridge open science policies with open hardware innovation and enable the more equal, flexible, and distributed infrastructure needed to achieve the global SDG agenda.

References

Abuzairi, Tomy, Nur Imaniati Sumantri, Ahli Irfan, and Ridho Maulana Mohamad. 2021. 'Infrared Thermometer on the Wall (IThermowall): An Open Source and 3-D Print Infrared Thermometer for Fever Screening'. *HardwareX* 9 (April): e00168. https://doi.org/10.1016/j.ohx.2020.e00168.

Arancio, Julieta. 2021. 'Open Hardware: A Key for Accelerating Science and Technology towards the U.N. Sustainable Development Goals (SDGs)', September. https://doi.org/10.5281/ZENODO.5415527.

Arancio, Julieta. 2021. 'Opening Up The Tools For Doing Science: The Case Of The Global Open Science Hardware Movement'. *International Journal of Engineering, Social Justice, and Peace* 8 (2): 1–27. https://doi.org/10.24908/ijesjp.v8i2.13997.

———. 2022. 'Diversifying Technology Transfer Tools to Increase the Impact of Academic Research'. *Institute for Policy Research, University of Bath* (blog). 2022. https://blogs.bath.ac.uk/iprblog/2021/12/10/diversifying-technology-transfer-tools-to-increase-the-impact-of-academic-research/.

Arancio, Julieta, and Shannon Dosemagen. 2022. 'Bringing Open Source to the Global Lab Bench'. *Issues in Science and Technology*, 7 February 2022. https://issues.org/open-source-science-hardware-gosh-arancio-dosemagen/.

Aspesi, Claudio, and Amy Brand. 2020. 'In Pursuit of Open Science, Open Access Is Not Enough'. *Science* 368 (6491): 574–77. https://doi.org/10.1126/science.aba3763.

Awuni, Stephen, and George Essegbey. 2014. 'Developing an Enabling Scientific Equipment Policy in Africa: The Ghana Country Study'. Ghana: Council for Scientific and Industrial Research. http://csirspace.csirgh.com/handle/123456789/1951.

Ballard, David H., Udayabhanu Jammalamadaka, Kathleen W. Meacham, Mark J. Hoegger, Broc A. Burke, Jason A. Morris, Alexander R. Scott, et al. 2021. 'Quantitative Fit Tested N95 Respirator-Alternatives Generated With CT Imaging and 3D Printing: A Response to Potential Shortages During the COVID-19 Pandemic'. *Academic Radiology* 28 (2): 158–65. https://doi.org/10.1016/j.acra.2020.11.005.

Bell, Martin, and Keith Pavitt. 1993. 'Technological Accumulation and Industrial Growth: Contrasts Between Developed and Developing Countries'. *Industrial and Corporate Change* 2 (2): 157–210. https://doi.org/10.1093/icc/2.2.157.

Bentancor, Marcel, Sebastián Fernández, Federico Viera, Sarita Etcheverry, Carolina Poradosú, Pablo D'Angelo, Hernán Montemuiño, et al. 2021. 'LUCIA: An Open Source Device for Disinfection of N95 Masks Using UV-C Radiation'. *HardwareX* 9 (April): e00181. https://doi.org/10.1016/j.ohx.2021.e00181.

Bertello, Alberto, Marcel L.A.M. Bogers, and Paola De Bernardi. 2022. 'Open Innovation in the Face of the COVID-19 Grand Challenge: Insights from the Pan-European Hackathon "EUvsVirus"'. *R&D Management* 52 (2): 178–92. https://doi.org/10.1111/radm.12456.

Bezuidenhout, Louise. 2020. 'Africa, Laboratory Equipment and COVID-19 Response', May. https://doi.org/10.5281/ZENODO.3824105.

Bezuidenhout, Louise, Julian Stirling, Valerian L. Sanga, Paul T. Nyakyi, Grace A. Mwakajinga, and Richard Bowman. 2022. 'Combining Development, Capacity Building and Responsible Innovation in GCRF-funded Medical Technology Research'. *Developing World Bioethics*, March, dewb.12340. https://doi.org/10.1111/dewb.12340.

Bianchini, Stefano, Patrick Llerena, and Sofia Patsali. 2019. 'Demand-Pull Innovation in Science: Empirical Evidence from a Research University's Suppliers'. *Research Policy*, Articles initially published in Research Policy: X issue 1, 48 (December): 100005. https://doi.org/10.1016/j.repolx.2019.100005.

Bol, Thijs, Mathijs de Vaan, and Arnout van de Rijt. 2018. 'The Matthew Effect in Science Funding'. *Proceedings of the National Academy of Sciences* 115 (19): 4887–90. https://doi.org/10.1073/pnas.1719557115.

Bonvoisin, Jérémy, Jenny Molloy, Martin Häuer, and Tobias Wenzel. 2020. 'Standardisation of Practices in Open Source Hardware'. *Journal of Open Hardware* 4 (1): 2. https://doi.org/10.5334/joh.22.

Botero-Valencia, J.S., M. Mejia-Herrera, and Joshua M. Pearce. 2022. 'Design and Implementation of 3-D Printed Radiation Shields for Environmental Sensors'. *HardwareX* 11 (April): e00267. https://doi.org/10.1016/j.ohx.2022.e00267.

Bowser, Anne, Alex Long, Alexandra Novak, Alison Parker, and Michael Weinberg. 2021. 'Stitching Together a Solution: Lessons from the Open Source Hardware Response to COVID-19 | Wilson Center'. The Wilson Center. https://www.wilsoncenter.org/publication/stitching-together-solution-lessons-open-source-hardware-response-covid-19.

Brown, Azby, Pieter Franken, Sean Bonner, Nick Dolezal, and Joe Moross. 2016. 'Safecast: Successful Citizen-Science for Radiation Measurement and Communication after Fukushima'. *Journal of Radiological Protection* 36 (2): S82–101. https://doi.org/10.1088/0952-4746/36/2/S82.

Budroni, Paolo, Jean Claude-Burgelman, and Michel Schouppe. 2019. 'Architectures of Knowledge: The European Open Science Cloud'. *ABI Technik* 39 (2): 130–41. https://doi.org/10.1515/abitech-2019-2006.

Burgos, Daniel, ed. 2020. *Radical Solutions and Open Science: An Open Approach to Boost Higher Education*. Lecture Notes in Educational Technology. Singapore: Springer Singapore. https://doi.org/10.1007/978-981-15-4276-3.

Business Wire. 2020. 'Paige Receives FDA Clearance for the FullFocus^{TM} Viewer for Digital Pathology'. 21 July 2020. https://www.businesswire.com/news/home/20200721005369/en/Paige-Receives-FDA-Clearance-for-the-FullFocus%E2%84%A2-Viewer-for-Digital-Pathology.

Carminati, M., and G. Scandurra. 2021. 'Impact and Trends in Embedding Field Programmable Gate Arrays and Microcontrollers in Scientific Instrumentation'. *Review of Scientific Instruments* 92 (9): 091501. https://doi.org/10.1063/5.0050999.

Carrasco-Escobar, Gabriel, Kimberly Fornace, Daniel Wong, Pierre G. Padilla-Huamantinco, Jose A. Saldaña-Lopez, Ober E. Castillo-Meza, Armando E. Caballero-Andrade, et al. 2020. 'Open-Source 3D Printable GPS Tracker to Characterize the Role of Human Population Movement on Malaria Epidemiology in River Networks: A Proof-of-Concept Study in the Peruvian Amazon'. *Frontiers in Public Health* 8. https://doi.org/10.3389/fpubh.2020.526468.

Carver, Jeffrey C., Sandra Gesing, Daniel S. Katz, Karthik Ram, and Nicholas Weber. 2018. 'Conceptualization of a US Research Software Sustainability Institute (URSSI)'. *Computing in Science & Engineering* 20 (3): 4–9. https://doi.org/10.1109/MCSE.2018.03221924.

Chowdhury, Priyabrata, Sanjoy Kumar Paul, Shahriar Kaisar, and Md. Abdul Moktadir. 2021. 'COVID-19 Pandemic Related Supply Chain Studies: A Systematic Review'. *Transportation Research Part E: Logistics and Transportation Review* 148 (April): 102271. https://doi.org/10.1016/j.tre.2021.102271.

Collins, Joel T., Joe Knapper, Julian Stirling, Joram Mduda, Catherine Mkindi, Valeriana Mayagaya, Grace A. Mwakajinga, et al. 2020. 'Robotic Microscopy for Everyone: The OpenFlexure Microscope'. *Biomedical Optics Express* 11 (5): 2447–60. https://doi.org/10.1364/BOE.385729.

Costanza-Chock, Sasha. 2020. *Design Justice: Community-Led Practices to Build the Worlds We Need*. Information Policy. Cambridge, MA: The MIT Press.

Council on Health Research for Development (COHRED), Global Forum for Health Research (GFHR), and Special Programme for Research and Training in Tropical Diseases (TDR). 2008. 'CHANGING MINDSETS: Research Capacity Strengthening in Low-and Middle-Income Countries'. https://www.files.ethz.ch/isn/128230/2008_Changing_Mindsets.pdf.

Else, Holly. 2021. 'A Guide to Plan S: The Open-Access Initiative Shaking up Science Publishing'. *Nature*, April. https://doi.org/10.1038/d41586-021-00883-6.

ESSENCE on Health Research. 2014. 'Seven Principles for Strengthening Research Capacity in Low- and Middle-Income Countries: Simple Ideas in a Complex World'. http://www.cohred.org/wp-content/uploads/2012/09/ESSENCE-2014.pdf.

Ferrari, Tiziana, Diego Scardaci, and Sergio Andreozzi. 2018. 'The Open Science Commons for the European Research Area'. In *Earth Observation Open Science and Innovation*, edited by Pierre-Philippe Mathieu and Christoph Aubrecht, 43–67. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-65633-5_3.

Fisher, E. 2013. 'The Power of Purchase: Addressing Sustainability through Public Procurement'. *European Procurement & Public Private Partnership Law Review* 8 (1): 2–7. https://doi.org/10.21552/EPPPL/2013/1/157.

Flanagan, Sarah T., and David H. Ballard. 2020. '3D Printed Face Shields: A Community Response to the COVID-19 Global Pandemic'. *Academic Radiology* 27 (6): 905–6. https://doi.org/10.1016/j.acra.2020.04.020.

Gadsby, Erica Wirrmann. 2011a. 'Research Capacity Strengthening: Donor Approaches to Improving and Assessing Its Impact in Low- and Middle-Income Countries'. *The International Journal of Health Planning and Management* 26 (1): 89–106. https://doi.org/10.1002/hpm.1031.

———. 2011b. 'Research Capacity Strengthening: Donor Approaches to Improving and Assessing Its Impact in Low- and Middle-Income Countries'. *The International Journal of Health Planning and Management* 26 (1): 89–106. https://doi.org/10.1002/hpm.1031.

Gallup, Nicole, Adam M. Pringle, Shane Oberloier, Nagendra G. Tanikella, and Joshua M. Pearce. 2020. 'Parametric Nasopharyngeal Swab for Sampling COVID-19 and Other Respiratory Viruses: Open Source Design, SLA 3-D Printing and UV Curing System'. *HardwareX* 8 (October): e00135. https://doi.org/10.1016/j.ohx.2020.e00135.

García-Villar, Cristina. 2021. 'A Critical Review on Altmetrics: Can We Measure the Social Impact Factor?' *Insights into Imaging* 12 (1): 92. https://doi.org/10.1186/s13244-021-01033-2.

Geuna, Aldo, and Lionel J.J. Nesta. 2006. 'University Patenting and Its Effects on Academic Research: The Emerging European Evidence'. *Research Policy* 35 (6): 790–807. https://doi.org/10.1016/j.respol.2006.04.005.

Gibney, Elizabeth. 2016. '"Open-Hardware" Pioneers Push for Low-Cost Lab Kit'. *Nature* 531 (7593): 147–48. https://doi.org/10.1038/531147a.

Global Forum for Health Research (GFHR), and World Health Organization. 2000. 'Global Forum for Health Research : An Overview'. World Health Organization. https://apps.who.int/iris/handle/10665/66474.

Global Open Science Hardware (GOSH) Community. 2016. 'GOSH Manifesto'. Gathering for Open Science Hardware. 2016. http://openhardware.science/gosh-manifesto/.

———. 2018. *GOSH Community Roadmap*. http://openhardware.science/wp-content/uploads/2017/12/GOSH-roadmap-smll.pdf.

Goel, Vinod K, Ekaterina Koryukin, Mohini Bhatia, and Priyanka Agarwal. 2004. *Innovation Systems : World Bank Support of Science and Technology Development.* World Bank Working Paper 32. Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/15026.

Hanna, Matthew G., Victor E. Reuter, Orly Ardon, David Kim, Sahussapont Joseph Sirintrapun, Peter J. Schüffler, Klaus J. Busam, et al. 2020. 'Validation of a Digital Pathology System Including Remote Review during the COVID-19 Pandemic'. *Modern Pathology* 33 (11): 2115–27. https://doi.org/10.1038/s41379-020-0601-5.

Health Innovation Lab. 2020. 'GORGAS Tracker - Project: Malaria and Human Mobility in the Peruvian Amazon'. https://github.com/healthinnovation/gorgas_tracker.

Heikkinen, I.T.S., H. Savin, J. Partanen, J. Seppälä, and J.M. Pearce. 2020. 'Towards National Policy for Open Source Hardware Research: The Case of Finland'. *Technological Forecasting and Social Change* 155 (June): 119986. https://doi.org/10.1016/j.techfore.2020.119986.

Hippel, Eric von. 1976. 'The Dominant Role of Users in the Scientific Instrument Innovation Process'. *Research Policy* 5 (3): 212–39.

Hohlbein, Johannes, Benedict Diederich, Barbora Marsikova, Emmanuel G. Reynaud, Séamus Holden, Wiebke Jahr, Robert Haase, and Kirti Prakash. 2022. 'Open Microscopy in the Life Sciences: Quo Vadis?' *Nature Methods* 19 (9): 1020–25. https://doi.org/10.1038/s41592-022-01602-3.

Hubbard, Benjamin R., and Joshua M. Pearce. 2020. 'Conversion of Self-Contained Breathing Apparatus Mask to Open Source Powered Air-Purifying Particulate Respirator for Fire Fighter COVID-19 Response'. *HardwareX* 8 (October): e00129. https://doi.org/10.1016/j.ohx.2020.e00129.

ITU. 2021. 'Connectivity in the Least Developed Countries: Status Report'. Office of the High Representative for the Least Developed Countries, Landlocked Developing Countries and Small Island Developing States. https://www.un.org/ohrlls/news/connectivity-least-developed-countries-status-report-2021.

Iyer, Adithi R. 2018. 'Authorship Trends in The Lancet Global Health'. *The Lancet Global Health* 6 (2): e142. https://doi.org/10.1016/S2214-109X(17)30497-7.

Kauttu, Pietari, and Luis Felipe Murillo. 2017. 'Open Hardware as an Experimental Innovation Platform: Preliminary Research Questions and Findings'. CERN IdeaSquare Journal of Experimental Innovation, June, 26 Pages. https://doi.org/10.23726/CIJ.2017.462.

Kinsella, Cormac M., Pauline Dianne Santos, Ignacio Postigo-Hidalgo, Alba Folgueiras-González, Tim Casper Passchier, Kevin P. Szillat, Joyce Odeke Akello, Beatriz Álvarez-Rodríguez, and Joan Martí-Carreras. 2020. 'Preparedness Needs Research: How Fundamental Science and International Collaboration Accelerated the Response to COVID-19'. Edited by Seema Lakdawala. *PLOS Pathogens* 16 (10): e1008902. https://doi.org/10.1371/journal.ppat.1008902.

Knapper, Joe, Julian STIRLING, Joel Collins, Samuel Mcdermott, Valerian Sanga, Paul Nyakyi, Grace Anyelwisye, et al. 2021. 'Transitioning from Academic Innovation to Viable Humanitarian Technology: The Next Steps for the OpenFlexure Project'. In *2021 IST-Africa Conference (IST-Africa)*, 1–11.

Lall, Sanjaya. 1992. 'Technological Capabilities and Industrialization'. *World Development* 20 (2): 165–86. https://doi.org/10.1016/0305-750X(92)90097-F.

Leonelli, S. 2018. 'Implementing Open Science: Strategies, Experiences and Models'. Report. European Commission. https://ore.exeter.ac.uk/repository/handle/10871/31337.

Lewis, David, and Allison Martell. 2021. 'Donors Bet a U.S. Firm Could Transform Disease Testing in Africa. Then COVID-19 Hit'. *Reuters Special Report*, 01 2021. https://www.reuters.com/investigates/special-report/health-coronavirus-africa-cepheid/.

Liscia, Daniel S., Donata Bellis, Elena Biletta, Mariangela D'Andrea, Giorgio A. Croci, and Umberto Dianzani. 2020. 'Whole-Slide Imaging Allows Pathologists to Work Remotely in Regions with Severe Logistical Constraints Due to Covid-19 Pandemic'. *Journal of Pathology Informatics* 11 (1): 20. https://doi.org/10.4103/jpi.jpi_32_20.

Luis Felipe R., Murillo, Pietari Kauttu, Pujol Priego Laia, Wareham Jonathan, and Katz Andrew. 2019. 'Open Hardware Licences: Parallels and Contrasts : Open Science Monitor Case Study'. *Open Science Monitor, European Commission*, November. https://helda.helsinki.fi/handle/10138/312235.

Maia Chagas, André. 2018. 'Haves and Have Nots Must Find a Better Way: The Case for Open Scientific Hardware'. *PLOS Biology* 16 (9): e3000014. https://doi.org/10.1371/journal.pbio.3000014.

Maia Chagas, Andre, Jennifer C. Molloy, Lucia L. Prieto-Godino, and Tom Baden. 2020. 'Leveraging Open Hardware to Alleviate the Burden of COVID-19 on Global Health Systems'. *PLOS Biology* 18 (4): e3000730. https://doi.org/10.1371/journal.pbio.3000730.

Maina, M. B., U. Ahmad, H. A. Ibrahim, S. K. Hamidu, F. E. Nasr, A. T. Salihu, A. I. Abushouk, et al. 2020. '20 Years of African Neuroscience: Waking a Sleeping Giant'. bioRxiv. https://www.biorxiv.org/content/10.1101/2020.06.03.131391v1.

Malekzadeh, Arianne, Kathleen Michels, Celia Wolfman, Nalini Anand, and Rachel Sturke. 2020. 'Strengthening Research Capacity in LMICs to Address the Global NCD Burden'. *Global Health Action* 13 (1): 1846904. https://doi.org/10.1080/16549716.2020.1846904.

Malkin, Robert, and Allison Keane. 2010. 'Evidence-Based Approach to the Maintenance of Laboratory and Medical Equipment in Resource-Poor Settings'. *Medical & Biological Engineering & Computing* 48 (7): 721–26. https://doi.org/10.1007/s11517-010-0630-1.

Manoj, Aluri, Monami Bhuyan, Swarup Raj Banik, and Mamilla Ravi Sankar. 2021. '3D Printing of Nasopharyngeal Swabs for COVID-19 Diagnose: Past and Current Trends'. *Materials Today: Proceedings* 44: 1361–68. https://doi.org/10.1016/j.matpr.2020.11.505.

McClintock, David S., Jacob T. Abel, and Toby C. Cornish. 2022. 'Whole Slide Imaging Hardware, Software, and Infrastructure'. In *Whole Slide Imaging: Current Applications and Future Directions*, edited by Anil V. Parwani, 23–56. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-83332-9_2.

Medrano, Alberto, Ángel Serra, and Carlos Soto. 2017. 'KiCad, Herramienta de Software Libre de Modelado de Circuitos Impresos Para El Desarrollo de Hardware'. *Ciencia e Ingeniería* 38 (2): 177–86.

Miljković, Nadica, Ana Trisovic, and Limor Peer. 2022. 'Towards FAIR Principles for Open Hardware', February. https://doi.org/10.5281/zenodo.5524414.

Minja, Happiness, Christian Nsanzabana, Christine Maure, Axel Hoffmann, Susan Rumisha, Olumide Ogundahunsi, Fabio Zicker, Marcel Tanner, and Pascal Launois. 2011. 'Impact of Health Research Capacity Strengthening in Low- and Middle-Income Countries: The Case of WHO/TDR Programmes'. *PLOS Neglected Tropical Diseases* 5 (10): e1351. https://doi.org/10.1371/journal.pntd.0001351.

Moran, Anna, Helen Haines, Nicole Raschke, David Schmidt, Alison Koschel, Alexandre Stephens, Cynthia Opie, and Susan Nancarrow. 2019. 'Mind the Gap: Is It Time to Invest in Embedded Researchers in Regional, Rural and Remote Health Services to Address Health Outcome Discrepancies for Those Living in Rural, Remote and Regional Areas?' *Australian Journal of Primary Health* 25 (2): 104–7. https://doi.org/10.1071/PY18201.

Mukhopadhyay, Sanjay, Adam L. Booth, Sarah M. Calkins, Erika E. Doxtader, Samson W. Fine, Jerad M. Gardner, Raul S. Gonzalez, Kamran M. Mirza, and Xiaoyin (Sara) Jiang. 2020. 'Leveraging Technology for Remote Learning in the Era of COVID-19 and Social Distancing'. *Archives of Pathology & Laboratory Medicine* 144 (9): 1027–36. https://doi.org/10.5858/arpa.2020-0201-ED.

National Academies of Sciences, Engineering, and Medicine (NASE). 2018. *Open Science by Design: Realizing a Vision for 21st Century Research*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/25116.

National Science Foundation (NSF) and National Center for Science and Engineering Statistics. 2020. 'Academic Institution Profiles – Rankings by Total R&D Expenditures'. 2020. .https://ncsesdata.nsf.gov/profiles/site?method=rankingbysource&ds=herd.

Nchinda, Thomas C. 2002. 'Research Capacity Strengthening in the South'. *Social Science & Medicine* 54 (11): 1699–1711. https://doi.org/10.1016/S0277-9536(01)00338-0.

Nel, Holly A, Trishan Naidoo, Emmanuel O Akindele, Tamuka Nhiwatiwa, Oluniyi O Fadare, and Stefan Krause. 2021. 'Collaboration and Infrastructure Is Needed to Develop an African Perspective on Micro(Nano)Plastic Pollution'. *Environmental Research Letters* 16 (2): 021002. https://doi.org/10.1088/1748-9326/abdaeb.

Nicholson, Kyle, Ashley Henke-Adams, Daniel M. Henke, Alexxai V. Kravitz, and Hiram A. Gay. 2021. 'Modified Full-Face Snorkel Mask as COVID-19 Personal Protective Equipment: Quantitative Results'. *HardwareX* 9 (April): e00185. https://doi.org/10.1016/j.ohx.2021.e00185.

Nikolopoulos, Konstantinos, Sushil Punia, Andreas Schäfers, Christos Tsinopoulos, and Chrysovalantis Vasilakis. 2021. 'Forecasting and Planning during a Pandemic: COVID-19 Growth Rates, Supply Chain Disruptions, and Governmental Decisions'. *European Journal of Operational Research* 290 (1): 99–115. https://doi.org/10.1016/j.ejor.2020.08.001.

Nyemba, Wilson R., Able Mashamba, and Charles Mbohwa. 2017. 'Equipment Maintenance Challenges and Solutions for Capacity Building and Sustainability in the Training of Engineers: The Case for the University of Zimbabwe'. *Procedia Manufacturing*, International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2017, 23-25 January 2017, Kruger, 7 (January): 303–8. https://doi.org/10.1016/j.promfg.2016.12.075.

Nyemba, Wilson R., Charles Mbohwa, and Keith F. Carter. 2021. 'Access to Modern Technology: Smart Partnerships for Research and Practice'. In *Bridging the Academia Industry Divide: Innovation and Industrialisation Perspective Using Systems Thinking Research in Sub-Saharan Africa*, edited by Wilson R. Nyemba, Charles Mbohwa, and Keith F. Carter, 167–87. EAI/Springer Innovations in Communication and Computing. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-70493-3_8.

Oberloier, S., N. Gallup, and J.M. Pearce. 2022. 'Overcoming Supply Disruptions during Pandemics by Utilizing Found Hardware for Open Source Gentle Ventilation'. *HardwareX* 11 (April): e00255. https://doi.org/10.1016/j.ohx.2021.e00255.

Open Source Hardware Association (OSHWA). 2010. 'Open Source Hardware Definition (English)'. Open Source Hardware Association. 2010. https://www.oshwa.org/definition/.

OSTP. 2022. *Memorandum: Ensuring Free, Immediate, and Equitable Access to Federally Funded Research*.

Ottinger, Gwen. 2010. 'Buckets of Resistance: Standards and the Effectiveness of Citizen Science'. *Science, Technology, & Human Values* 35 (2): 244–70. https://doi.org/10.1177/0162243909337121.

Papworth, Sarah K., Nils Bunnefeld, Katie Slocombe, and E. J. Milner-Gulland. 2012. 'Movement Ecology of Human Resource Users: Using Net Squared Displacement, Biased Random Bridges and Resource Utilization Functions to Quantify Hunter and Gatherer Behaviour: *Movement Ecology of Human Resource Users*'. *Methods in Ecology and Evolution* 3 (3): 584–94. https://doi.org/10.1111/j.2041-210X.2012.00189.x

Patel, Ankush, Ulysses G.J. Balis, Jerome Cheng, Zaibo Li, Giovanni Lujan, David S. McClintock, Liron Pantanowitz, and Anil Parwani. 2021. 'Contemporary Whole Slide Imaging Devices and Their Applications within the Modern Pathology Department: A Selected Hardware Review'. *Journal of Pathology Informatics* 12 (1): 50. https://doi.org/10.4103/jpi.jpi_66_21.

Patnaik, Jayshree, and Bhaskar Bhowmick. 2019. 'Revisiting Appropriate Technology with Changing Socio-Technical Landscape in Emerging Countries'. *Technology in Society* 57 (May): 8–19. https://doi.org/10.1016/j.techsoc.2018.11.004.

Pearce, Joshua M. 2012. 'Building Research Equipment with Free, Open-Source Hardware'. *Science* 337 (6100): 1303–4. https://doi.org/10.1126/science.1228183.

———. 2015. 'Quantifying the Value of Open Source Hard-Ware Development'. *Modern Economy* 06 (01): 1–11. https://doi.org/10.4236/me.2015.61001.

———. 2016. 'Return on Investment for Open Source Scientific Hardware Development'. *Science and Public Policy* 43 (2): 192–95. https://doi.org/10.1093/scipol/scv034.

———. 2018. 'Sponsored Libre Research Agreements to Create Free and Open Source Software and Hardware'. *Inventions* 3 (3): 44. https://doi.org/10.3390/inventions3030044.

———. 2020a. 'A Review of Open Source Ventilators for COVID-19 and Future Pandemics'. *F1000Research* 9 (April): 218. https://doi.org/10.12688/f1000research.22942.2.

———. 2020b. 'Economic Savings for Scientific Free and Open Source Technology: A Review'. *HardwareX* 8 (October): e00139. https://doi.org/10.1016/j.ohx.2020.e00139.

———. 2021. *Create, Share, and Save Money Using Open-Source Projects*. New York: McGraw Hill.

———. 2022. 'Strategic Investment in Open Hardware for National Security'. *Technologies* 10 (2): 53. https://doi.org/10.3390/technologies10020053.

Pearce, Joshua, & Jun Yu Qian, 2022. Economic Impact of DIY Home Manufacturing of Consumer Products with Low-cost 3D Printing from Free and Open Source Designs. *European Journal of Social Impact and Circular Economy*, 3(2), 1-24. https://doi.org/10.13135/2704-9906/6508

Petersen, Emily, and Joshua Pearce. 2017. 'Emergence of Home Manufacturing in the Developed World: Return on Investment for Open-Source 3-D Printers'. *Technologies* 5 (1): 7. https://doi.org/10.3390/technologies5010007.

Piwowar, Heather, Jason Priem, Vincent Larivière, Juan Pablo Alperin, Lisa Matthias, Bree Norlander, Ashley Farley, Jevin West, and Stefanie Haustein. 2018. 'The State of OA: A Large-Scale Analysis of the Prevalence and Impact of Open Access Articles'. *PeerJ* 6 (February): e4375. https://doi.org/10.7717/peerj.4375.

Ramoutar-Prieschl, Rakeshnie, and Sepo Hachigonta. 2020. 'The Sustainable Management of Research Equipment'. In *Management of Research Infrastructures: A South African Funding Perspective*, edited by Rakeshnie Ramoutar-Prieschl and Sepo Hachigonta, 77–90. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-37281-1_7.

Ravindran, Sandeep. 2020. 'How DIY Technologies Are Democratizing Science'. *Nature* 587 (7834): 509–11. https://doi.org/10.1038/d41586-020-03193-5.

reGOSH. 2022. 'Laboratorio Agroecologico Abierto'. 2022. https://regosh.libres.cc/proyectos/lab-agroeco-abierto/.

Retamero, Juan Antonio, Jose Aneiros-Fernandez, and Raimundo G. del Moral. 2020. 'Complete Digital Pathology for Routine Histopathology Diagnosis in a Multicenter Hospital Network'. *Archives of Pathology & Laboratory Medicine* 144 (2): 221–28. https://doi.org/10.5858/arpa.2018-0541-OA.

Rey-Mazón, Pablo, Hagit Keysar, Shannon Dosemagen, Catherine D'Ignazio, and Don Blair. 2018. 'Public Lab: Community-Based Approaches to Urban and Environmental Health and Justice'. *Science and Engineering Ethics* 24 (3): 971–97. https://doi.org/10.1007/s11948-018-0059-8.

Ross-Hellauer, Tony, Stefan Reichmann, Nicki Lisa Cole, Angela Fessl, Thomas Klebel, and Nancy Pontika. 2022. 'Dynamics of Cumulative Advantage and Threats to Equity in Open Science: A Scoping Review'. *Royal Society Open Science* 9 (1): 211032. https://doi.org/10.1098/rsos.211032.

Santhosh, Rahul, and Sudha Yadav. 2021. 'Low Cost Multipurpose UV-C Sterilizer Box for Protection against COVID'19'. In *2021 International Conference on Artificial Intelligence and Smart Systems (ICAIS)*, 1495–98. Coimbatore, India: IEEE. https://doi.org/10.1109/ICAIS50930.2021.9395752.

Scheffler, Matthias, Martin Aeschlimann, Martin Albrecht, Tristan Bereau, Hans-Joachim Bungartz, Claudia Felser, Mark Greiner, et al. 2022. 'FAIR Data Enabling New Horizons for Materials Research'. *Nature* 604 (7907): 635–42. https://doi.org/10.1038/s41586-022-04501-x.

Schreiber, Kelsey L., Christopher B. Barrett, Elizabeth R. Bageant, Abebe Shimeles, Joanna B. Upton, and Maria DiGiovanni. 2022. 'Building Research Capacity in an Under-represented Group: The STAARS Program Experience'. *Applied Economic Perspectives and Policy*, July, aepp.13310. https://doi.org/10.1002/aepp.13310.

Shahatha Al-Mashhadani, Abdulrazak F., Muhammad Imran Qureshi, Sanil S. Hishan, Mohd Shamsuri Md Saad, Yamunah Vaicondam, and Nohman Khan. 2021. 'Towards the Development of Digital Manufacturing Ecosystems for Sustainable Performance: Learning from the Past Two Decades of Research'. *Energies* 14 (10): 2945. https://doi.org/10.3390/en14102945.

Skrzypczak, Noah G., Nagendra G. Tanikella, and Joshua M. Pearce. 2020. 'Open Source High-Temperature RepRap for 3-D Printing Heat-Sterilizable PPE and Other Applications'. *HardwareX* 8 (October): e00130. https://doi.org/10.1016/j.ohx.2020.e00130.

Srai, Jagjit Singh, Mukesh Kumar, Gary Graham, Wendy Phillips, James Tooze, Simon Ford, Paul Beecher, et al. 2016. 'Distributed Manufacturing: Scope, Challenges and Opportunities'. *International Journal of Production Research* 54 (23): 6917–35. https://doi.org/10.1080/00207543.2016.1192302.

Stirling, Julian, and Richard Bowman. 2021. 'The COVID-19 Pandemic Highlights the Need for Open Design Not Just Open Hardware'. *The Design Journal* 24 (2): 299–314. https://doi.org/10.1080/14606925.2020.1859168.

Stirling, Julian, Kaspar Bumke, Joel Collins, Vimal Dhokia, and Richard Bowman. 2022. 'HardOps: Utilising the Software Development Toolchain for Hardware Design'. *International Journal of Computer Integrated Manufacturing*, February, 1–13. https://doi.org/10.1080/0951192X.2022.2028188.

Stirling, Julian, Valerian L. Sanga, Paul T. Nyakyi, Grace A. Mwakajinga, Joel T. Collins, Kaspar Bumke, Joe Knapper, Qingxin Meng, Samuel McDermott, and Richard Bowman. 2020. 'The OpenFlexure Project. The Technical Challenges of Co-Developing a Microscope in the UK and Tanzania'. In *2020 IEEE Global Humanitarian Technology Conference (GHTC)*, 1–4. https://doi.org/10.1109/GHTC46280.2020.9342860.

Trytten, Cindy, Martin Wale, Michael Hayes, and Bev Holmes. 2019. 'Lessons Learned from a Health Authority Research Capacity-Building Initiative'. *Healthcare Management Forum* 32 (5): 259–65. https://doi.org/10.1177/0840470419849468.

Tsimidou, Maria Z., Stella A. Ordoudi, Fani Th Mantzouridou, Nikolaos Nenadis, Tamara Stelzl, Michael Rychlik, Nastasia Belc, and Claudia Zoani. 2022. 'Strategic Priorities of the Scientific Plan of the European Research Infrastructure METROFOOD-RI for Promoting Metrology in Food and Nutrition'. *Foods* 11 (4): 599. https://doi.org/10.3390/foods11040599.

UNESCO. 2021. 'UNESCO Science Report: The Race against Time for Smarter Development'. Paris: UNESCO Publishing.

United Nations Conference on Trade and Development (UNCTAD). 2021. 'Technology and Innovation Report 2021'. Technology and Innovation Report. https://unctad.org/system/files/official-document/tir2020_en.pdf.

United Nations Educational, Scientific and Cultural Organization (UNESCO). 2021. 'UNESCO Recommendation on Open Science'. https://en.unesco.org/science-sustainable-future/open-science/recommendation.

United Nations (UN). 2015. 'Goal 9: Industry, Innovation and Infrastructure'. The Global Goals. 2015. https://globalgoals.org/goals/9-industry-innovation-and-infrastructure/.

U.S. Food and Drug Administration (FDA). 2020. 'FDA Allows Marketing of First Whole Slide Imaging System for Digital Pathology'. FDA. 24 March 2020. https://www.fda.gov/news-events/press-announcements/fda-allows-marketing-first-whole-slide-imaging-system-digital-pathology.

Veselovská, Lenka. 2020. 'Supply Chain Disruptions in the Context of Early Stages of the Global COVID-19 Outbreak'. *Problems and Perspectives in Management* 18 (2): 490–500. https://doi.org/10.21511/ppm.18(2).2020.40.

Vicente-Saez, Ruben, Robin Gustafsson, and Lieve Van den Brande. 2020. 'The Dawn of an Open Exploration Era: Emergent Principles and Practices of Open Science and Innovation of University Research Teams in a Digital World'. *Technological Forecasting and Social Change* 156 (July): 120037. https://doi.org/10.1016/j.techfore.2020.120037.

Wijnen, Bas, Emily J. Hunt, Gerald C. Anzalone, and Joshua M. Pearce. 2014. 'Open-Source Syringe Pump Library'. Edited by Giorgio F. Gilestro. *PLoS ONE* 9 (9): e107216. https://doi.org/10.1371/journal.pone.0107216.

Williams, K, and B Davis. 2019. 'Public and Private Disinvestments in Historically Black Colleges and Universities.' Washington, DC. https://www.acenet.edu/Documents/Public-and-Private-Investments-and-Divestments-in-HBCUs.pdf.

Wittbrodt, B.T., A.G. Glover, J. Laureto, G.C. Anzalone, D. Oppliger, J.L. Irwin, and J.M. Pearce. 2013. 'Life-Cycle Economic Analysis of Distributed Manufacturing with Open-Source 3-D Printers'. *Mechatronics* 23 (6): 713–26. https://doi.org/10.1016/j.mechatronics.2013.06.002.

World Health Organization (WHO). 2016a. *Malaria Microscopy Quality Assurance Manual*. World Health Organization. https://apps.who.int/iris/handle/10665/204266.

———. 2016b. *Malaria Microscopy Quality Assurance Manual-Version 2*. Geneva: World Health Organization. https://apps.who.int/iris/handle/10665/336010.

———. 2021. 'Global Technical Strategy for Malaria 2016-2030, 2021 Update'. https://www.who.int/publications-detail-redirect/9789240031357.

Julieta Arancio is a postdoctoral researcher at the Center for Science, Technology and Society, Drexel University (US). After getting her Ph.D. in 2021 in Argentina, she is currently funded by the Alfred P. Sloan Foundation to work on a case study of the OpenFlexure Microscope (UK). Julieta is interested in how open source and open innovation can transform the way we do science and technology towards more democratic knowledge production. She co-founded the Latin American network of free-open source technologies for research and education (reGOSH) and co-organizes the mentorship program "Open Hardware Makers", recently funded by Code for Science and Society.

Mayra Morales Tirado is a postdoctoral research associate at the Manchester Institute of Innovation Research in a collaborative research project that aims to understand research assessments, standards, and practices in different fields of research. Her doctoral research explores the effects of an international mobility instrument in Mexico. Before coming to Manchester, she was teaching at undergraduate and postgraduate level in the Economics and Management Division, as well as in the Science and Engineering Division at the University of Guanajuato. Additionally, she was Chief in Studies and Scientific-Technology Policy for the Council of Science and Technology of Guanajuato.

Joshua M. Pearce is the John M. Thompson Chair in Information Technology and Innovation at the Thompson Centre for Engineering Leadership & Innovation. He holds appointments at Ivey Business School and the Department of Electrical & Computer Engineering at Western University in Canada. His research concentrates on the use of open source appropriate technology (OSAT) to find collaborative solutions to problems in sustainability and to reduce poverty. His research spans areas of engineering of solar photovoltaic technology, open hardware, and distributed recycling and additive manufacturing (DRAM) using RepRap 3-D printing, but also includes policy and economics.

Acknowledgements

This work was supported by the Alfred P. Sloan Foundation, the Thompson Endowment and the Natural Sciences and Engineering Research Council of Canada.