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Citizen Science for Transformative Air Quality Policy in Germany and Niger

Robert Lepenies [1,*] and Ibrahim Sidi Zakari [2]

[1] Helmholtz Centre for Environmental Research-UFZ, Department of Environmental Politics, 0431 Leipzig, Germany
[2] Laboratory of Mathematics and Applications, Department of Mathematics and Computer Science, Faculty of Sciences and Techniques, Abdou Moumouni University, 10662 Niamey, Niger; sidizakariibrahim@gmail.com
* Correspondence: robert.lepenies@ufz.de

Abstract: How can citizen science projects advance the achievement of transformative air quality-related Sustainable Development Goals (SDGs) in Germany and Niger? We investigate the promise of using citizen-generated data (CGD) as an input for official SDG monitoring and implementation in a multidisciplinary project, based on activities undertaken in Niger and Germany ranging from surveys, action research, policy and legislative analysis and environmental monitoring in Niamey and Leipzig, respectively. We critically describe and evaluate the great potential, but very limited actual use of CGD sources for these global goals in both contexts from technical and policy perspectives. Agenda 2030 provides an opportunity to tackle indoor and outdoor air quality in a more integrated and transformative perspective. However, we find this agenda to be remarkably absent in air quality policy and monitoring plans. Likewise, we find no meaningful links of existing citizen science initiatives to official air quality policy. We propose how SDGs-aligned citizen science initiatives could make major contributions to environmental and health monitoring and public debate, especially in the wake of the COVID-19 pandemic. This however requires researchers to more strategically link these initiatives to policymakers and policy frameworks, such as SDG indicators and the governance structures in which they are embedded.

Keywords: citizen science; urban air quality; Sustainable Development Goals; data crowdsourcing; low-cost sensors; air pollution; environmental policy analysis; SDG indicators; statistical analysis; sustainability transformations

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1. Introduction

Citizen science (CS) is gaining attention among academics, particularly in the context of monitoring and implementing the United Nations Sustainable Development Goals (SDGs) [1] at the national and international level [2–5].

A number of CS initiatives—even if they are not explicitly framed as contributing to the SDGs—are specifically focused on tackling air pollution [6,7]. Air pollution remains the most important environmental cause of premature death in Europe [8]. At the same time, many African cities are facing rapid urbanization. Areas with high traffic volumes coupled with high population densities are most at risk to air pollution levels that exceed the limits recommended by the World Health Organization especially when it comes to levels of particulate matter ($PM_{2.5}$ and PM_{10}) which are exacerbated by dust storm, biomass burning and industrial activities [9]. Among West African countries, from 1990 to 2017, Niger registered the highest average annual population-weighted $PM_{2.5}$ [10]. These higher levels of $PM_{2.5}$ could be explained by the fact that from 1990 to 2017, more than 98 percent of the population used solid fuels (for cooking, heating or lighting) in Niger. Hence, both indoor and outdoor air quality is a major concern for the well-being of Nigerien citizens, while air quality monitoring is not systematically available.

Germany, in international comparison, has relatively high air quality standards, with air quality improving slightly in the last two decades, mostly driven by strict European legislation mandating clean air plans and extensive environmental monitoring [11]. Indeed, transgressions of agreed upon ambient air quality standards have been the subject of vigorous public and policy discussion in Germany [12,13]. Air pollutants pose environmental and health challenges and stem mostly from road traffic, as well as industrial production, agriculture and heating systems. Air quality in Germany has nearly exclusively been a challenge of ambient (outdoor) air quality. Yet, with the advent of the novel coronavirus and its transmission pathway via aerosols, public attention is increasingly (re-)focusing on indoor air quality—an area where there is no comprehensive legislation. Despite multiple air quality frameworks at different levels of governance in Germany, and despite a dense network of air quality monitoring stations throughout the country and sophisticated statistical models, considerable data, policy and awareness gaps remain.

Citizen science has been heralded as a particularly promising vehicle through which disaggregated data and the required scale and resolution could be provided for tackling environmental (monitoring) challenges. It has also been lauded for its potential to make scientific engagement more widely accessible and raising awareness about emerging issues such as air pollution.

2. Research Questions

The SDGs provide a holistic and integrated agenda with political targets and indicators that are explicitly interlinked. Air pollution is a case in point: the SDGs cover both ambient air pollution as well as indoor air pollution. They include targets and indicators on mortality from air pollution (3.9.1), access to clean fuels (7.1.2) as well as air quality in cities (11.6.2). With this, Agenda 2030 complements other calls for "transformative change" and "systemic and integrated policy action" as for example in the Sixth Global Environment Outlook (GEO-6) which urges an integrated treatment of air quality challenges that combines climate, health and environmental objectives [14]. Why, then, are we not seeing such integrated policy action in practice? Additionally, what could fill the monitoring and implementation gaps? Fritz et al. [15] point out that SDG indicators 3.9.1 and 11.6.2 "provide neither the actionable information that cities and communities need to manage their local conditions, nor do they contribute to an increased understanding of the health impacts of air pollution." They suggest that citizen science "can fill this gap through the novel application of traditional sensors such as Palmes' diffusion tubes and the ongoing efforts to develop reliable low-cost electrochemical sensors" (pp. 927–928). It is precisely these aspects that we investigate in our project. How can CS fill monitoring and implementation gaps in the two highly different contexts of Germany and Niger?

We investigate the promise of using citizen-generated data (CGD) as an input for official SDG monitoring and implementation in a multidisciplinary project, based on activities undertaken in Niger and Germany ranging from surveys, action research, policy and legislative analysis and environmental monitoring in the localities of Niamey (Niger) and Leipzig (Germany), respectively. The theoretical framework is motivated both by debates on "transformations to sustainability" which stress the need to take seriously "diverse knowledges, plural pathways and the essentially political nature of transformation" [16] and by the literature on sustainability transitions research [15–17]. Which approaches enable new actors and novel practices to become involved in air quality policy processes and debates? Which approaches can improve both the quality of monitoring ("data gaps") as well as awareness ("awareness gaps") and science–policy–society partnerships ("policy gaps")? Frameworks such as "transition management" have helped identify potential governance innovations, experiments and instruments. The vast majority of research on either citizen science projects or sustainability transitions has been undertaken in the global North (and by researchers from the global North). As a project led by principal investigators (PIs) from Niger and Germany, we emphasize the value of international comparisons of CS projects in both the Global North and the Global South using a common overarching framework. Such a comparison of two highly disparate socio-economic realities, in Germany and Niger, is challenging, as will be detailed below. Yet, such a global question is precisely in line with the ambition of the SDGs: the key question relates to how citizen science initiatives—whether in Germany or Niger—can be adapted to specific social, cultural and political contexts in order to support Agenda 2030 in both the narrow technical sense, as well as in this overarching transformative ambition.

3. Materials and Methods

In order to implement the SDGs, much of research itself needs to be transformative and experimental, ideally integrating technical and policy perspectives together with relevant stakeholders—for example, by drawing on "sustainability science" [17,18]. It is with this ambition that we started exploring the potential for citizen science (CS) to aid SDGs implementation in two (presumably) vastly different social, political and cultural contexts as part of a Global Young Academy project. Our interdisciplinary grant brought together disciplines from statistics, environmental policy analysis and political philosophy. Rather than representing a citizen science project itself, the project is a multi-perspectival reflection on CS. In 2017, we began analyzing the suggestions from the Stockholm Environment Institute [1] about how citizen science could help with the definition, monitoring or implementation of specific SDGs targets. We decided to focus on closing three types of gaps: "data gaps", "awareness gaps" and "policy gaps", addressing questions of technical, cultural and political fit, respectively. Transition research suggests that closing such gaps could result in transformative policy change [16].

After this process and during the 2017–2020 period, we combined techniques such as online quizzes and questionnaires (via Google forms) with activities such as capacity building workshops, interviews, video-based storytelling, conferences, exhibitions (Figure 1), smartphone-based photos crowdsourcing, sensing air quality using low-cost sensors (Figure 2) and interactive maps for enhancing public understanding of air pollution-related SDGs. For instance, two (2) data collection campaigns about cooking technologies and fuels were conducted in Niamey, respectively, from February to March 2017 and from January to February 2019. Participants in these campaigns were bachelor's students (from the Faculty of Sciences and Techniques at Abdou Moumouni University of Niamey) who were enrolled in the ICT course. Students were engaged in the data collection phases of our project and were recruited on a voluntary basis and were trained on smartphones and tablet-based data collection tools (particularly Google forms features for collecting qualitative and quantitative data as well as photos). In 2017, 337 students (and 306 students in 2019) responded to the online quizzes and questionnaires about the issue of air pollution and SDGs; they uploaded photos (via the questionnaires) on cooking technologies and fuels used in Niamey.

(**a**) (**b**)

Figure 1. *Cont.*

(**c**) (**d**)

Figure 1. (**a**) Public conference (at Abdou Moumouni University) on citizen science, open data and Sustainable Development Goals (SDGs) as part of the UNESCO World Science Day for Peace and Development (2018); (**b**) environmental citizen science exhibition during the Innovation for Development (I4Dev) side event (as part of the African Union Summit) 8–10 July 2019, Niamey (Niger); (**c**) a citizen scientist promoting a t-shirt message "The research group on citizen science and open data serving the SDGs needs you! Please send us your photos and comments related to one or more SDGs to cs4sdg@gmail.com"; (**d**) interview with a woman using woodfuel for cooking in indoor environment with children. Source: Sidi Zakari.

Figure 2. Overview of pollution (air and noise) sensing materials and additional accessories (GPS, temperature and humidity measurement devices) when meeting citizen science projects in Leipzig, Germany. Low-cost sensors used at Helmholtz UFZ are described in [19].

The lessons learned from the 2017 data collection campaign contributed to improving the 2019 one and participants of the first campaign contributed (as research collaborators) to the definition of research objectives as well as the data collection, analysis and in the training of new cohorts of citizen scientists.

As additional small-scale pilot air quality monitoring campaign (via low-cost sensors) was conducted in December 2019 in Leipzig. Unfortunately, it was impossible to upscale this initiative by involving citizen scientists due to the COVID-19 pandemic.

Portable low-cost sensors are able to measure and to provide real-time data on particulate matters (PM_1, $PM_{2.5}$, PM_{10}), different gases including nitrogen dioxide (NO_2), carbon monoxide (CO), sulfur dioxide (SO_2), ozone(O_3) as well as volatile organic compounds (VOCs). Moreover, they feature connectivity to both Android and IOS smartphones (running on apps developed by UFZ-Leipzig or third-party apps like Flow developed by Plume

Lab company for its next-generation Flow 2 sensor) via a Bluetooth connection. Air quality measurements (pollutants concentrations) are reported in micrograms per cubic meter ($\mu g/m^3$) and PM sizes are expressed in micron or micrometer.

Online quizzes and questionnaire-based data analysis was performed in real time via Google forms data analytics tools. Crowdsourced photos were analyzed and interpreted by student citizen scientists (bachelor's to PhD levels) and their families. This mix of methods was experimental: most action research-oriented activities were undertaken in Niamey, Niger, together with students at Abdou Moumouni University (AMU). The project did not involve the collection of personal data of the participants. Moreover, a code of ethics for the project was available to the participants (based on the AMU's ICT charter as well as the charter of ethics and deontology of public universities of Niger. We also promote norms and best practices in terms of addressing privacy concerns, high quality scientific methodology, research integrity, responsible data collection, data sharing and governance, conflicts management, ways to acknowledge the contributions of participants and intellectual property.

At the same time, a policy and legal feasibility analysis for including citizen science projects into official SDGs monitoring and implementation was undertaken with a focus on the city of Leipzig, Germany, drawing on previous research with low-cost air quality sensors. This analysis consisted of a scoping of air quality citizen science projects, (non-standardized) expert interviews with citizen science project leaders, document analysis of relevant air quality policy frameworks at multiple levels of governance from the communal (Leipzig city), land (Sachsen), national (Germany) and EU to international levels. This text was developed in several project meetings, joint conference attendance, joint expert interviews as well as a research stay in Leipzig in December 2019.

While only some of the described activities are themselves citizen science activities in the narrow sense, our approach allows us to triangulate the components for SDGs-aligned CS projects, especially as we combine a comparative political feasibility analysis with insights from short environmental monitoring campaigns in Niamey and Leipzig. Therefore, while others focus on the role of CS indicators at the UN level [20], we look at monitoring and implementation within two UN members states at the communal level. This inclusion of policy and governance aspects means that we do not report on a specific citizen science project, but rather on interlocking pilot activities and reflections of what we consider an SDG-aligned CS that can produce, as others have called for, "good enough" data [21] while engaging with issues that matter to citizens across different dimensions. In both sites, we attempted to explore the conditions under which CS campaigns can contribute to achieving the transformative ambition of Agenda 2030, looking at:

1. Technical fit: exploring the feasibility of using citizen science methodology to address major air quality issues in the respective sites by closing "transformative data gaps".
2. Cultural fit: exploring the level of understanding of citizen science and air quality problems, closing "transformative awareness gaps".
3. Political fit: exploring the feasibility of linking to official SDGs reporting and implementation, closing "transformative policy gaps".

4. Results

4.1. A New Workflow for SDGs-Aligned CS Projects in Order to Enable Transformations

With the suggested workflow for SDGs-aligned CS projects (Figure 3), we build on Fritz et al. [15] who provided a roadmap for integrating CS into the formal SDG reporting mechanisms and who pointed out the fact that data from air pollution monitoring stations (as non-traditional data sources) are used by the World Health Organization (WHO) to model particulate matter (for Indicator 11.6.2: "Annual mean levels of fine particulate matter (e.g., $PM_{2.5}$ and PM_{10}) in cities (population weighted)"), which then feeds into Indicator 3.9.1: "Mortality rate attributed to household and ambient air pollution". Indeed, we regard indicator 3.9.1 as particularly promising to jumpstart discussions about transformative air quality policy because of its integrated nature [22]. However, it is important that the workflow also includes novel deliberative fora so that SDGs-aligned CS projects do not become technical exercises only—but so that they are meaningfully linked to political fora in which citizens can debate and deliberate the ends of air quality policy. We refer to a pathway towards more sustainable policies derived labeled "enabling approaches" [16] which focuses on "smaller actions that collectively, over time, shift system states in ways which may be unexpected" and which values the agency and emancipatory potential of new actors using novel practices. Hence, we see the purpose of SDGs-aligned activities as the threefold impact of raising data quality, awareness and leveraging science–policy–society partnerships.

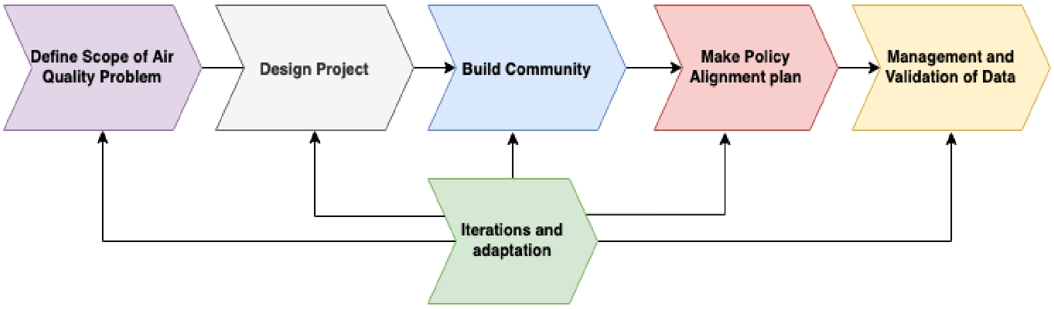


Figure 3. Workflow of an SDG-aligned Citizen Science project. Source: Authors (adapted from Fritz et al. [15], citizenscience.gov [23] and Bonney et al. [24]).

The importance of clean air has been enshrined in SDGs target 11.6 which aims "by 2030, [to] reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality [. . .]". In order to monitor progress towards this target, all countries will need to provide "high-quality, timely and accessible data, often in areas where very little data exists today" [1].

We argue that citizen science projects should pay particular attention to the novel stages 3 and 4 (building a community at the science–policy–society interface and more strategically aligning to formal SDGs monitoring frameworks) that we suggest adding here. This represents both a more enabling and strategic involvement of CS researchers and CS associations to directly link to relevant agencies, actors and frameworks, ideally around SDGs indicators. With this, we emphasize the link between environmental agencies and CS projects [25–27], but urge alignment with SDG-specific monitoring processes while considering the risks of misuse, underuse and abuse of (environmental) indicators through an integrative perspective [28]. We are only aware of one similar attempt in the Polish context [29] that proposes the use of the SDG indicators framework, together with sensor-based distributed input, to map urban air quality and health through development of a new indicator on pollen. In Figure 4, we describe more generally the role of CS projects in science–policy–society interactions that have a transformative ambition [30]. The yellow-shaded ellipse represents the ambitious vision of CS groups to not only influence the quality of monitoring ("data gaps") but also to build new partnerships ("policy gaps") where policy ends can be deliberated ("awareness gaps").

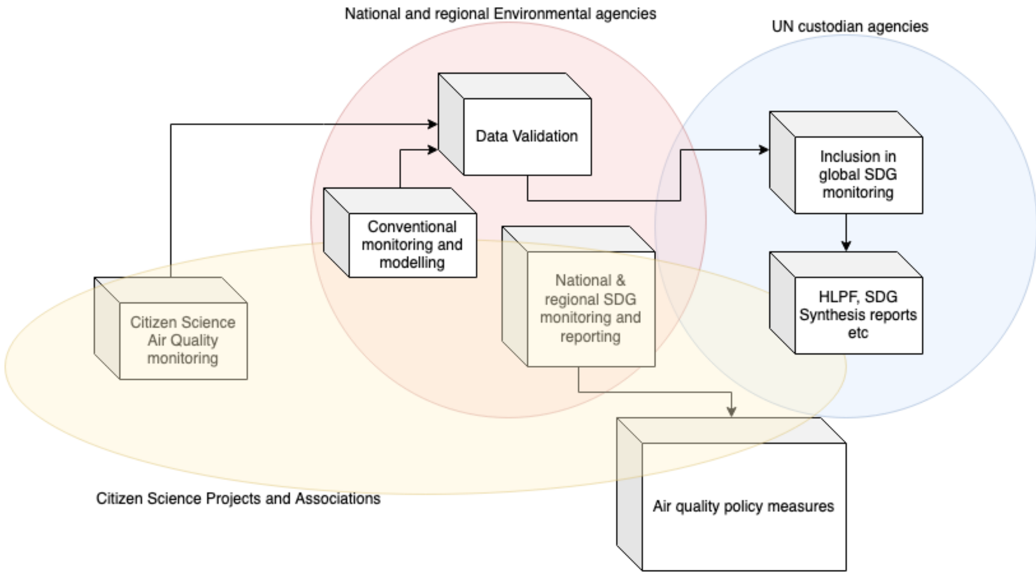


Figure 4. A schematic for more strategic involvement of citizen science (CS) projects.

4.2. Niamey: Clean Cooking Fuels and Technologies

Our CS approach aligns with the following seven SDGs targets 7.1, 7.2, 11.6, 11.b, 12.4, 12.8 and 12.a suggested by the Stockholm Environment Institute [1] about how citizen science approaches could help with the definition, monitoring or implementation of specific SDG targets. However, of course, different air quality challenges in different locations require different types of environmental data and monitoring. The primary question is: whose air quality problems matter? Additionally, here, platforms of deliberation and exchange—and not just technical solutions, are necessary.

The biggest air quality challenge in Niamey, Niger is related to the need for clean indoor cooking fuels, an issue intimately related to multidimensional and energy poverty [31]. At the national level, the Enquête Nationale sur les Conditions de Vie des Ménages et l'Agriculture (ECVM/A), also known as the National Household Living Conditions and Agriculture Survey (conducted in 2011 and 2014) is instructive here [32,33]. It revealed that in terms of energy for cooking, 74.5% of the workforce in the Nigerien middle class used collected wood fuel in 2011; compared to 69.7% in 2014. In addition, 24.2% of this class used purchased woodfuel in 2011 against 27.5% in 2014. Additionally, the majority of households (all levels of income and social classes considered) did not use a second or alternative fuel for cooking (charcoal, gas, electricity, kerosene, biomass, etc.). The use of such cooking fuels is responsible for severe health problems. In our pilot project, we investigated what activities could help fill a data, awareness and policy gap with respect to clean cooking fuels. In terms of policy and technical fit, a policy analysis revealed the aforementioned ECVM/A as a key data source for the establishment of the situation of reference of the SDGs in Niger and its related priority targets and metadata for indicators. The main legislation regulating air quality in Niger is Law 98-56 on environmental management [34] which, together with the national environmental and social development strategy, still constitutes the core of environmental legislation in Niger [35].

A contextually relevant policy framework was the Stratégie Nationale d'Accès aux Services Energétiques (National Strategy for Access to Modern Energy Services) which aimed to increase the percentage of the population with access to modern energy services. Citizen science projects that strive to make a transformative contribution to this challenge in Niger hence need to adapt to this reference framework, given the lack of other comprehensive frameworks [36]. While Niger has contributed two Voluntary National Reviews for the official UN reporting [37], none of the relevant indicators addressed here were reported upon.

With this in mind, students were asked to upload photos to a crowdsourced database about local cooking fuels and technologies (Figure 5). This crowdsourcing activity registered 610 photos from 305 contributors and aimed at monitoring access to affordable, clean and reliable energy services (SDG 7) in Niamey; additional details are provided in [38]. Students were asked to classify the crowdsourced photos in terms of the most polluting, the least polluting and the most used cooking technology in Niamey. Student answers were compared to WHO air quality recommendations [39].

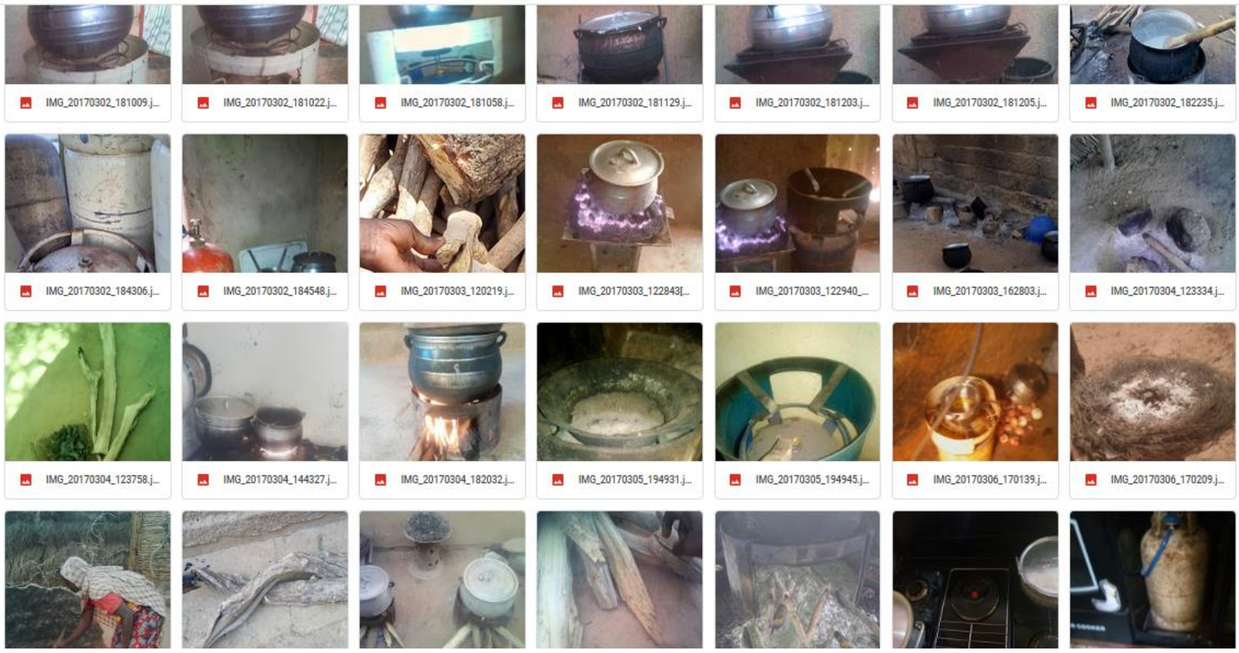
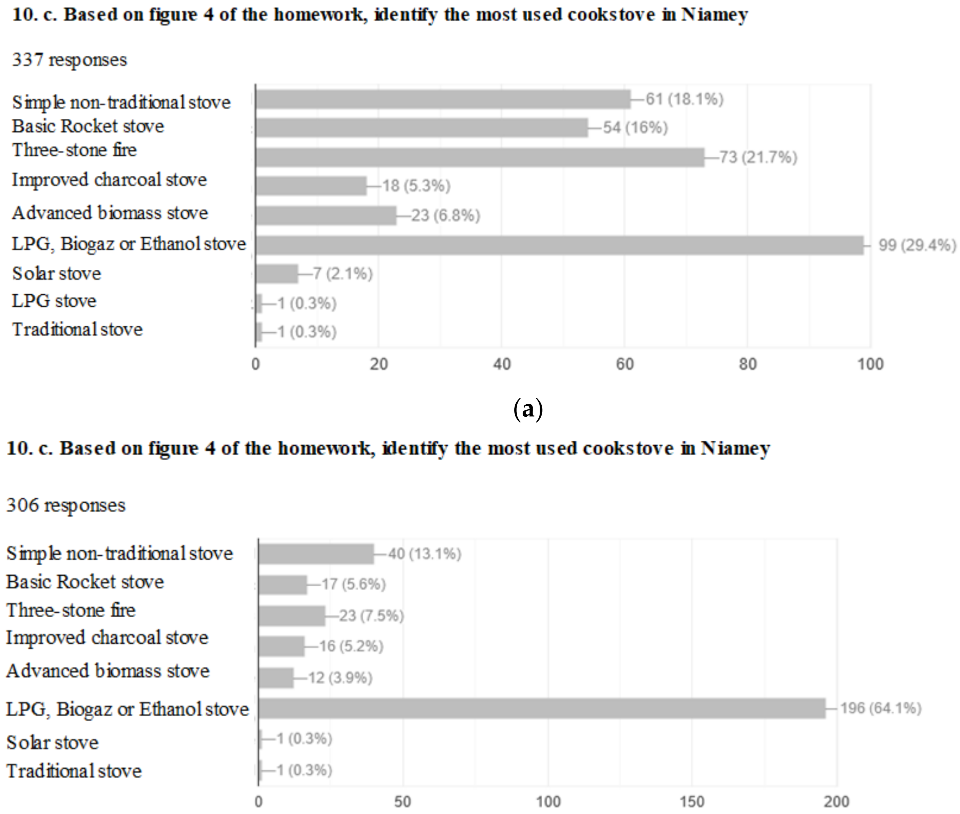


Figure 5. Overview of the crowdsourced photos database about cooking fuels and technologies used in the students' neighborhood. Source: Sidi Zakari.

Figure 6 revealed that in 2017, 29.4% of students identified LPG/biogas and ethanol as the most used cooking technology in Niamey followed by three-stone fire (identified by 21.7% of the respondents) and simple non-traditional stove (18.1% of the respondents). In 2019, 64.1% of students identified LPG/biogas and ethanol as the most used cooking technology in Niamey followed by simple non-traditional stove (identified by 13.1% of the respondents) and three-stone fire (identified by 7.5% of the respondents). This pilot initiative (as a case study) showed potential to be upscaled so that it can complement existing data sources and official statistics for the definition and monitoring of the aforementioned SDGs indicators 7.1.2 and 11.6.2 with a specifically local air quality challenge.

In order to guarantee high-quality data, we regularly assess our data management plan as well as providing training and capacity building activities for our research collaborators. Moreover, our data management plan takes into account FAIR principles; however, to date the data are not publicly available online. We aim to publish the data and corresponding metadata in trustworthy online repositories that comply with these principles and under the Creative Commons Attribution License 4.0 International (CC BY 4.0).

Furthermore, the pilot also had a pedagogical/civic component: as Niamey students represent the future generation of scientists, policymakers, civil society, etc. who are expected to be role models for raising awareness about the impacts of air pollution, it was considered both appropriate and beneficial to discuss the benefits of adopting clean cooking technologies in their communities.



(b)

Figure 6. (**a**) Identification of the most used cooking technology in Niamey (2017); (**b**) identification of the most used cooking technology in Niamey (2019). Source: Sidi Zakari.

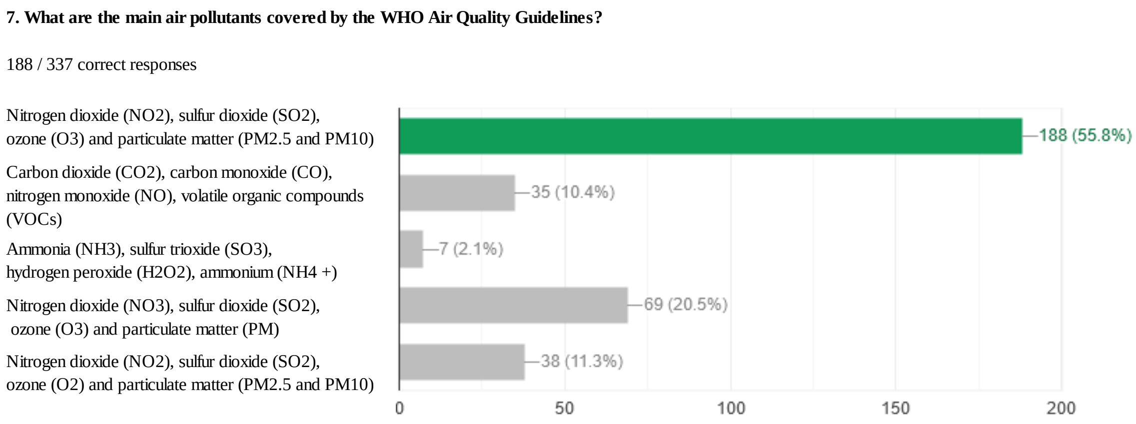
4.3. Niamey: Awareness About Air Pollution

In the above activities, Niamey-based students were involved—as much as possible—as citizen scientists, contributing to problem definition and choice of the data collection methods. They voluntarily contributed their time, effort, and resources (smartphones, mobile internet, digital cameras) toward aspects of the scientific research (research question, data collection and analysis, etc.) or the development of data-driven solutions in collaboration with Nigerien scientists. It was learned in the project that in order to have transformative potential, closer links to official monitoring frameworks would have been necessary.

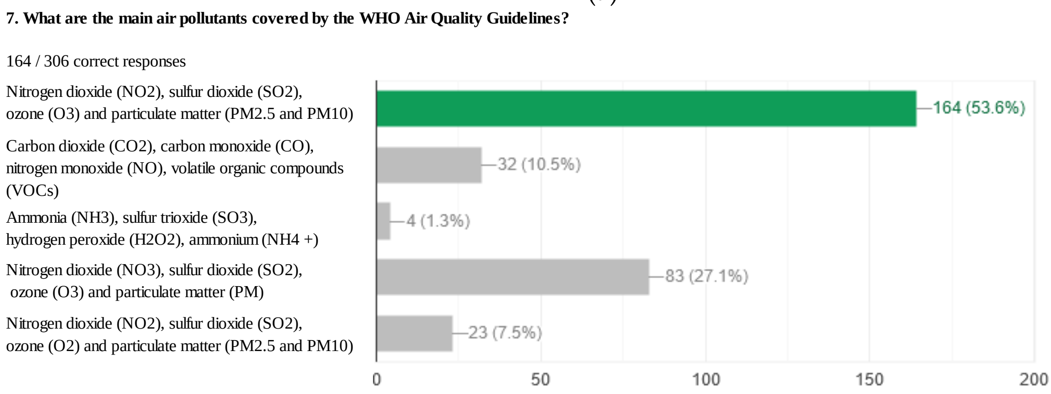
There are various ways in which CS activities can optimize citizen engagement [40]. Given limited funds, extending the project to include citizens beyond students and trying these options was not possible in our case. It was, however, possible to involve families of students, often residing in peri urban areas of Niamey for interpretation. In the Niamey site, it became quickly apparent that the involved citizens were not familiar with air pollution-related SDGs, spurring important deliberations about appropriate levels of air pollution. A further institutionalization of such deliberations (e.g., a deliberative air quality platform) would have been desirable. An even bigger—unfortunately unrealized—ambition was to establish an international platform to bring citizens from Leipzig and Niamey into communication with another to learn about policy, awareness and data gaps within an overarching framework of the SDGs. Similarly, it was not feasible to link these data to responsible environmental agencies for capacity reasons. Yet, there are two gaps ("policy gap" and "awareness gap") that could be filled with novel partnerships and deepened participatory platforms (see also [20]).

As there are next to no data on this, two UN SDGs awareness assessments were conducted via online quizzes in 2017 and 2019 as part of the hands-on homework for bachelor's students enrolled within the ICT course at the faculty of sciences and techniques

(Abdou Moumouni University); we, respectively, registered 337 respondents (86.1% males and 13.9% females) and 306 respondents (78.1% males and 21.9% females). Figure 7 illustrates the question number seven of these quizzes which is "What are the main air pollutants covered by the WHO Air Quality Guidelines?". This figure shows that 55.8% of the respondents (53.6% of respondents in 2019) have found the correct response in 2017; this is *nitrogen dioxide* (NO_2), *sulfur dioxide*(SO_2), *ozone* (O_3) *and particulate matter* ($PM_{2.5}$ *and* PM_{10}).



(**a**)



(**b**)

Figure 7. (**a**) Responses to the question number seven of the SDGs awareness quiz (2017); (**b**) Responses to the question number seven of the SDGs awareness quiz (2019).

Our local activities showed that prior to monitoring-specific CS activities, other baseline information about air pollution awareness, one of the most important air quality challenges, was required. However, discussions with students since 2018 showed that indicator 3.9.1, which explicitly draws on health impacts of air pollution, could be a potential entry point into a wide-ranging discussion (the aforementioned deliberation platform) about the importance of indoor and outdoor clean air. We could not identify other Nigerien citizen science initiatives with an air quality focus, nor could we identify air quality policy frameworks that explicitly drew on either citizen science despite engagement with the statistical community [41]. These realizations led to the drafting of the workflow for SDG-aligned CS initiatives based on the experience in Niger (Figure 3).

Mobile and web-based apps are currently under development for raising awareness about health impacts of air pollution and for promoting clean cooking technologies and fuels in Niger.

4.4. Participatory Air Quality Monitoring in Leipzig and Niamey

One of the recommendations from a previous vocational training organized at Abdou Moumouni University (from 1 March to 3 March 2017) and entitled "Harnessing the power of mobile phone apps for air pollution monitoring in Niger" was to pursue awareness raising on the impacts of air pollution and partnerships for implementing mobile apps and low-cost sensors, which could reduce local data gaps related to SDGs indicator 11.6.2 (Annual mean levels of fine particulate matter ($PM_{2.5}$ and PM_{10}) in cities (population weighted)). Indeed, Figure 8 gives an overview of the evolution of this indicator for $PM_{2.5}$ during the 1990 to 2017 period.

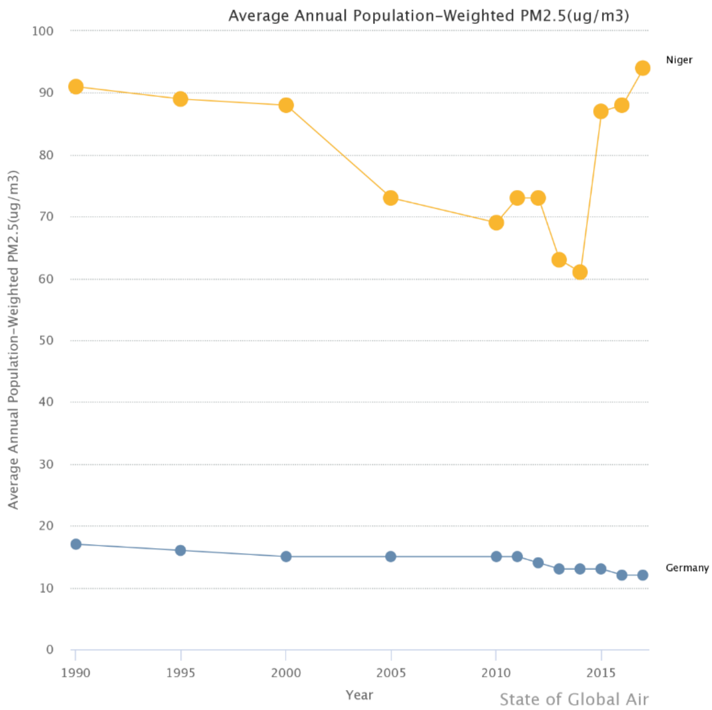


Figure 8. Evolution of the average annual population-weighted $PM_{2.5}$ in Germany (blue) and Niger (yellow) from 1990 to 2017. Source: Authors' computation from [42].

For Germany, PM2.5 levels are decreasing (17 $\mu g/m^3$ in 1990 to 12 $\mu g/m^3$ in 2017) while they are increasing in Niger (91 $\mu g/m^3$ in 1990, 61 $\mu g/m^3$ in 2014 and 94 $\mu g/m^3$ in 2017). The long-term objective for this indicator is a value of 6.3 $\mu g/m^3$ [43,44].

Although it is important to monitor air quality particularly in urban areas, fixed monitoring stations for pollutants like $PM_{2.5}$ and PM_{10} are nonexistent in Niamey or are very few; as we will see, there are three (3) of them in Leipzig (Figure 9) and 28 in Saxony/Sachsen.

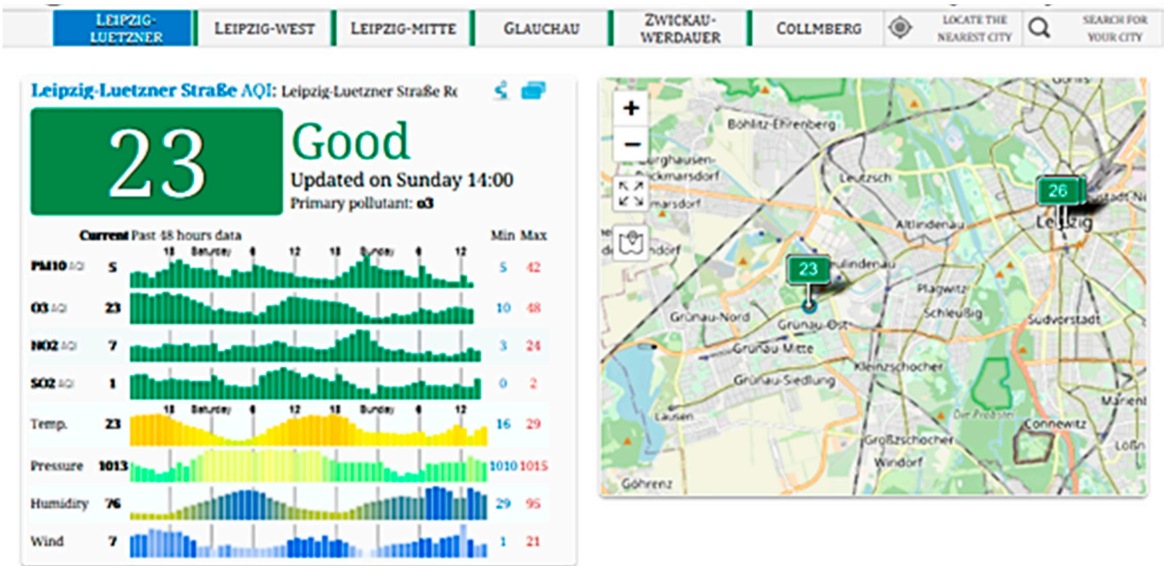


Figure 9. Example of real-time air quality index (AQI = 23), main pollutants and meteorological parameters' statistical distributions for one of the three Leipzig city's air quality monitoring stations. Source: Authors' search from The World AirQuality Project [45].

There is potential for low-cost citizen science campaigns in both Niamey and Leipzig that could inform inhabitants about air quality even without relying on fixed monitoring stations; live air quality reports and air quality forecasts (Figures 10 and 11) together with deployment of low-cost sensors could create a dense network of measuring points in both localities, closing important data gaps. This network combined with data science or machine learning methods could complement or improve the quality of the existing official data by providing new pathways to obtain accurate and real-time information. This then could be linked to health recommendation provided by citizen scientists, as in Figure 11 (where high pollution leads to a recommendation to not engage in outdoor sports, or to bring small children outside due to poor air quality that is higher than the maximum limit for 24 h established by WHO).

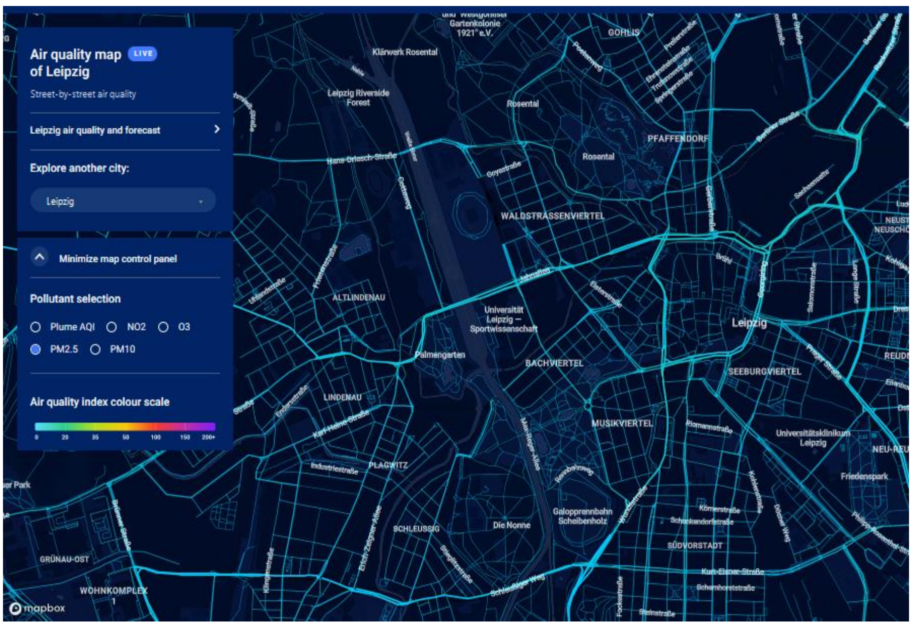


Figure 10. Example of live street-by-street air quality map of the city of Leipzig (for $PM_{2.5}$). Source: Authors' search from Plume Labs Germany Map [46].

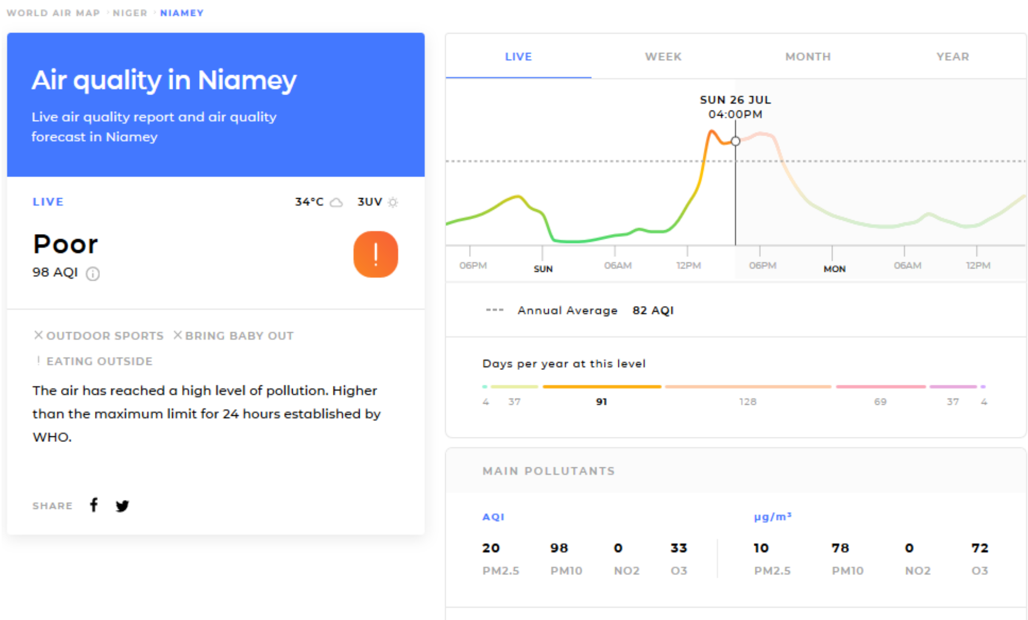


Figure 11. Example of live air quality reports and air quality forecasts for the city of Niamey. Source: Authors' search from Plume Labs Niger Map [47].

A common challenge identified during our pilot air quality monitoring campaign in Leipzig and Niamey is related to the reliability of low-cost sensors (Figure 2) used to measure local air pollution levels, particularly in terms of sensitivity to extreme weather conditions (wind speed, temperature, humidity) or lack of capacity to measure very high or very low pollutant concentrations. For future projects, citizen scientists should be made aware of these limitations (particularly for emerging next-generation devices). The specifically hot climatic conditions in Niamey pose a particular problem for low-cost sensors. We were able to identify only one reliable low-cost sensor able to withstand high temperatures in Niamey while also withstanding sub-zero temperatures in Leipzig (Plume Labs sensor). In Europe and the US, there are many different platforms where data from mobile low-cost sensors can be uploaded. In 2017, a survey of apps available on Google Play (Android apps) and App Store (iphone, ipad, etc.) revealed that while popular apps such as Breezo Meter and Plume Air Report were identified as the most rated apps for measuring and forecasting air quality worldwide, they do not provide information on air quality for the majority of African countries including Niger. Still, our project showed that using the same sensor in both localities could contribute to official SDGs monitoring of the PM-related SDGs indicator and thereby close data gaps. The bigger problem is the link to the official monitoring framework (policy gap) and a lack of fora to discuss air quality issues (awareness gap)—and this, surprisingly, is true for both Niger and Germany.

As mentioned above, there is no comprehensive air quality regulation in Niger. It is therefore of utmost importance for researchers to link directly to agencies. One example to construct links between researchers and policy is the annual Salon de l'Agriculture, l'Hydraulique et de l'Elevage (SAHEL Niger) which is a national gathering where photos and videos on emerging air quality monitoring technologies and clean cooking innovations are debated. It is also an opportunity to engage with policymakers, civil society, NGOs, manufacturers and citizens (customers) on air pollution-related SDGs and the benefits of switching from solid fuels to LPG or solar cooking technologies. It is important to raise the importance of both citizen science and an SDGs framing of air quality policies in fora like these to strengthen science–policy–society interactions.

4.5. Citizen Science and SDGs: Little Evidence for Links in Germany

Citizen science in Germany is well established—yet it is surprising that there is no meaningful link from CS projects to SDG monitoring and implementation. Germany has a national CS strategy that is mostly driven by academics [48] which proposes recommendations financing and integrating CS projects into scientific processes, into education concepts for sustainable development and to strengthen CS application in decision-making processes. Ostermann et al. [49] analyzed 96 CS projects registered on the official website of the German Federal Ministry for Education and Research (BMBF) and pointed out the role of digitalization of projects and internet use in the rapid growth of CS in recent years. Yet, it seems that this blooming community is not having an impact at the official SDG policy and monitoring level. Our analysis of federal documents shows that the relevant national SDG strategy has made no mention of citizen science in the last decade [50,51].

Additional details about CS linkages with the SDGs can be found [52–55]. Many different groups and campaigns use low-cost air sensors for environmental monitoring [25–27]; however, there are no known instances of CS projects substantially influencing SDG reporting or implementation at the national level. In Germany, we mapped and contacted all major participatory air quality monitoring initiatives and either undertook document analysis of their policy impact or conducted interviews with their organizers. We found that no initiative had explicit links to SDG implementation. We also encountered the problem that initiatives were rarely operating continuously: after conclusion of a specific funding cycle, activities that could generate CGD relevant for monitoring were simply halted or merged into larger data repositories. While the level of innovation in the projects is high, and while there are dedicated volunteers who help solve environmental problems, this is not done within an SDG framing (see [56] on hackAIR; but see also Luftdaten.info, sensebox or I-SPEX).

4.6. Multi-Level Policy Analysis for Leipzig, Saxony, Germany, EU: No Mention of the SDGs in Policy Frameworks—A Missed Opportunity

The SDGs are a global framework that already integrates the various dimensions and values of clean air. This can best be shown in indicator 3.9.1 (Mortality from air pollution) which is a calculated indicator that combines the health impact from indoor and outdoor air pollution. However, in all the relevant policy documents that we analyzed for the City of Leipzig, the federal state of Saxony/Sachsen or even at the federal level of Germany, there is no mention of this indicator of air policy programming. As the regulatory discussion is so heavily framed around ambient air quality, it is surprising that indoor air quality is not comprehensively legislated in Germany, a problem that only few stakeholders have raised throughout the years [57]. Yet, SDG indicator 3.9.1, ignored at the local level, is making precisely this conceptual link. We argue that this is a major missed opportunity for policymakers and a more informed debate on transformative air quality policy. The problem of pressure related to ambient air quality is high in Leipzig. In surveys, air pollution is consistently rated as one of the areas of high concern in Leipzig, with satisfaction in perceived air quality shrinking in the last years [58,59]. This is interesting, because this decrease in satisfaction is accompanied by an objective improvement in environmental air quality data nearly throughout the whole city [60]. Even though the air is getting better, people are unhappier about this pollution. Indeed, air quality is a topic where age groups have different views on both problem salience as well as on appropriate political measures [59]. These intergenerational differences harbor conflict potential. As described above, road traffic (especially by Diesel vehicles) is the major source of air pollution in Leipzig. Indeed, survey responses about potential bans of Diesel vehicles in the city of Leipzig skew heavily depending on the respondents' age, with a vast majority of young people supporting Diesel car bans, and a vast majority of more senior citizens strongly opposing bans of Diesel cars. The SDGs, with their explicit focus on merging health, environmental and economic perspectives and the ambition to "leave no one behind" could be the ideal basis from which to negotiate these different conversations towards sustainable transformations of air quality policy. Another surprising health impact relates to wood stove pollution in residential areas, a significant but underreported air pollution issue in Germany that is mostly due to lifestyle choices. While not decisive in Leipzig, such wood or pellet stoves are responsible for significant particulate matter pollution in different residential areas in Germany, and are often found in more affluent neighborhoods [61].

For the City of Leipzig, we analyzed the last decade of the clean air policy framework from 2009 until 2019 and associated monitoring [62,63]. It is positive to see that at the general communal level, there has been an official endorsement and reframing of urban sustainability according to the Agenda 2030 [64] together with NGOs interest in the matter of sustainability indicators [65].

Due to sophisticated and demanding European legislation, there is a continuous air quality policy program with detailed measures (up to 50 measures) that both the federal state of Saxony and the city of Leipzig are implementing. However, these programs are not linked to any items of Agenda 2030, but are solely linked to European legislation and its German implementation, the Bundes-Immissionsschutzgesetz (BImSchV), the ordinance on national commitments for the reduction of certain atmospheric pollutions. These clean air programs are very closely linked to monitoring and indicator systems, that again are managed at the state and city level.

4.7. Better Monitoring Systems through Citizen Science in Leipzig?

Theoretically, there is great potential to mend the gap between monitoring and policy implementation of the SDGs. Especially for the UN level, this has been highlighted by Fraisl et al. [66] and Fritz et al. [15], where the authors review how CS data could be used either as a primary or supplementary data source for the SDGs. They are very optimistic, claiming "it appears likely that indicators measuring issues that raise a concern among citizens and communities are more amenable to citizen science. The reason for this may be these issues affect or could affect their health, environment and quality of life." With regard to Indicator 11.6.2, they write that there are several CS projects that involve citizens in measuring $PM_{2.5}$ and PM_{10} and that "there are increasingly larger numbers of sensors being deployed by citizens that could contribute measurements to WHO's model". Concretely, air quality is a particularly interesting topic because here, indicators can be used "to fill spatial or temporal gaps in data (e.g., air quality reference stations can be coupled with citizen science data on air quality)".

Our policy analysis for Leipzig (and to some extent, this is applicable to Niamey) shows that the core problem remains that these data are not picked up by relevant agencies, that there are weak science–policy–society interactions and that institutionalized deliberation on air quality is lacking.

We analyzed all monitoring reports at the state and city level [67–70] together with relevant policy statements by local and regional environmental agencies and environmental ministries. We found no reference to the SDGs or citizen science in the reports surveyed. Even for accepting "good enough" data, there is a long way to go [20] and several strategies are needed (such as establishing communities of practice inside public administration or other strategies successfully undertaken [71]). There are also concrete legislative hurdles. Indeed, attempting to bring citizen-generated data into these monitoring and reporting schemes is particularly difficult as it is the BImSchV (and the associated data quality controls by TüV) that legislates about the specifics of monitoring. It is here that CS initiatives would have to show that their mobile/low-cost measures are compatible with a national legislative framework that looks only at fixed monitoring stations.

5. Discussion

In order to live up to the promise of helping implement the SDGs, the citizen science community should radically rethink how it engages with relevant policy actors and institutions at the local, regional and national level. In both Niamey and Leipzig, we encountered considerable cultural, political, social and legislative obstacles—with both CS and SDGs absent from integrated air quality policy discussions.

Even though on the face of it, Germany is doing relatively well in the environmental performance that impacts SDGs indicator 3.9.1 (mortality rate attributed to household and ambient air pollution), we find that there is a distinct lack of an integrated perspective on air quality. The lack of attention to indoor air quality is already impacting the country—namely, the lack of policy action on filtering and ventilation systems to deal with aerosol transmission of COVID-19 in public and private buildings as of early 2021. Likewise, there is a lack of citizen engagement with air quality topics, which may risk heightened conflicts between increasingly polarized views on air quality priorities.

Major challenges remain for Niger. A very high mortality rate is attributable to the joint effects of fuels used for cooking indoors and ambient outdoor air pollution. Outdoor air pollution does not seem to rank high in terms of political salience, even though we could not find data to support this.

While wood stove pollution is considerable in Germany, it is (as well as its socioeconomic impacts) largely ignored. Clean cooking fuels play no role for indoor air quality, with nearly 100% of the German population using clean cooking fuels and technologies for cooking [44] compared to less than 2% of the Nigerien population [43]. Through its clean air programs, Germany could increase efforts for achieving the long-term objective of 6.3 $\mu g/m^3$ for the indicator 11.6.2 (annual mean levels of fine particulate matter ($PM_{2.5}$ and PM_{10}) in cities (population weighted)), while for Niger this is very challenging as the country would need to move from solid fuels (biomass, charcoal, woodfuel) to non-solid fuels (LPG, ethanol, biogas, electricity, solar).

A transformative debate on air quality is needed in both localities. Additionally, in both, SDG-aligned CS campaigns could be an instrument to raise the quality of such discussions, to spur a sustainability transition based on an "enabling approach" that brings together actors in novel partnerships with new practices of sense-making about air quality [16,72]. It is precisely such novel partnerships that are also at the core of goal 17 of the SDGs (partnerships for the goals). Within such SDG-aligned citizen science air quality projects, behavioral change could be promoted using tools like interactive air quality quizzes [73] and apps—while also bringing together citizens to deliberate about air quality policy. At the core of these projects, citizen scientists could have the opportunity to use crowdsourced data to understand their own local air quality. For Niamey, we saw that the level of awareness about air pollution and SDGs in public universities of Niger could be improved by increasing the number of citizen science initiatives that involve young generations that will move into scientific roles. We believe that after this project, participants will be more aware about the issue of air pollution as well as the importance of switching from solid fuels (usually associated to dirty stoves) to non-solid ones (clean cooking fuels). Moreover, sustained support from government will certainly contribute to accelerate the adoption of clean cooking technologies and fuels.

In Europe, our hope is pinned on advances at the level of European environmental governance. Our analysis shows that given the absence of SDG-alignment and CS innovations at the regional level, maybe there can be innovations that could "trickle down" to national and regional contexts. Indeed, the Commission has repeatedly pushed for CS inclusion [74], e.g., in monitoring [75] while the European Environmental Agency is both proposing this theoretically, while also supporting applied CS projects (albeit without reference to the SDGs) [76].

Following Fritz et al. [15] we concur that more powerful associations are required that can systematically advocate for the interests and ambitions of CS. As we saw, the communities of CS and SDG statisticians are very separate.

Today, the world is not on track on for reaching the SDGs, and—due to COVID-19—is also facing serious set-backs in monitoring progress towards implementation. Building on CS experiences in Niger and Germany, we argue that post-COVID-19 CS initiatives can help contribute to the tackling of transformative air quality policy problems if they allow for a broad framing that tries to holistically integrate the multiple goals of the 2030 Agenda. CS initiatives on air pollution could advocate for covering both the quality of ambient air as well as the quality of indoor air with broader socio-economic concerns in both the global North and South. Yet, in order to make a meaningful contribution to both implementation and better monitoring, CS campaigns need to be conducted according to principles which we outlined above, namely: context-sensitive design; stakeholder involvement of monitoring agencies; links to policy problems and relevant policy frameworks as well as deliberative fora [75]. Furthermore, although the majority of participants in our project are students and researchers, we regularly conduct capacity building and training on several topics including citizen science approaches, the SDGs framework, health impacts of air pollution, air quality monitoring equipment, open data as well as digital data collection and analysis tools.

The SDGs provide an opportunity to think more holistically about the benefits of clean air—indoors and outdoors [77]. Recently, a group of Academies called for a new "Global Compact on Air Pollution". To some extent, we see that such a global compact already exists with the SDGs. We hence propose to think bigger: an overarching attention to clean air is needed with great intersectoral support. We need to think beyond silos (indoor/outdoor; environmental vs. human effects) and engage a broad coalition of actors with air quality topics. For this, CS initiatives for air quality can be suitable instruments, but need policy support, while also shifting their own mindsets—initiatives need to flexibly engage with the political, cultural and technical challenges we outlined, and start to collect and reflect on data from multiple sources. Mobile sensors are a great start here [19,78]. However, they also need to be durable (last beyond funding periods), truly participatory, and policy context sensitive (be designed such that they can feed into relevant policy frameworks).

Plans for sustaining the collaboration between citizens and scientists after the end of the project include: applying for additional funding so that we can upscale the current project, involving citizens in all phases of future projects (designing research questions and protocols, data collection, data analysis, research dissemination, etc.), co-construction of low-cost sensors, identification of emerging topics/issues to be investigated. Finally, our investigation revealed challenges and future research directions which include: financing of SDG-aligned CS initiatives with a transnational and transformative ambition; mainstreaming CS as an accepted methodology and source of data for SDGs monitoring and reporting; creating a trusted environment in which CS data are accepted as a credible source of inputs for statistical reporting at the national level; in-depth comparison of technologies (fixed and mobile stations vs low-cost sensors) in CS projects; CS around air pollution maps for major cities of Niger and throughout West Africa; mapping contextual strategies for involving citizen scientists in the monitoring and implementation of air pollution-related SDGs; analyzing the influence of extreme weather conditions on the reliability of air quality measurements; mainstreaming (big) data analysis skills within CS projects and public agencies.

6. Conclusions

In this project, we investigate the missing links between citizen science initiatives and SDG policy and monitoring frameworks. Statistical agencies in both countries and at the UN level are often reluctant to consider novel data sources despite some advances in this area. We find multiple context-specific reasons that hinder the adoption of citizen-generated data across levels of governance. Our analysis shows that apart from data gaps, there are significant awareness and policy gaps that SDGs-aligned CS projects could close. For both our cases in Western Europe and West Africa, we describe this as a major missed opportunity at the science–policy–society interface to engage in a more informed debate on transformative and integrated air quality policy.

Even though SDGs implementation in both Niger and Germany is lacking, Agenda 2030 provides the starting point as an international politically legitimated set of goals and monitoring practices that holds promise for cleaner air. Future plans for integrating indicators related to harmful pollutants like PM_1 can include data from next-generation low-cost sensors from CS initiatives. Going further, transformative air quality policy can be structured not just around existing indicators but also around the concrete governance settings in which these indicators are embedded (national, regional reporting structures). Effective SDG-aligned projects, for which we suggest a workflow, rely on the good will and support of statistical agencies and policymakers. Yet, it is the CS community that should intensify their efforts here: CS initiatives should strive to coproduce together with relevant agencies across levels of governance as much as possible. It is time for CS initiatives to become policy-astute and strategic, in order for individual projects to connect to policy initiatives. In this way, citizen science can contribute to defining targets and metrics on different levels, monitoring progress and implementing action. Yes, citizen science projects can play an important role in providing the data needed to monitor progress towards the SDGs; however, they could also be a site for open debate about conflicting policy propositions and the integrated nature of the SDGs.

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