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More Democratic Sustainability Governance through Participatory Knowledge Production? A Framework and Systematic Analysis

Evelien de Hoop [1,2]

[1] Copernicus Institute of Sustainable Devleopment, Utrecht University, 3584 CB Utrecht, The Netherlands; e.dehoop@uu.nl

[2] Athena Institute, Vrije Universiteit Amsterdam, 1081 HV Amsterdam, The Netherlands

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Abstract: This paper investigates how participatory knowledge production may contribute to more democratic sustainability governance. It develops an analytical framework in order to perform a systematic analysis of the GammaSense project in the Netherlands, on the measurement of gamma radiation by citizens. The paper first of all concludes that the way in which participation takes place throughout each and every stage of the knowledge production process, including technically complex issues such as the design of the measurement system and analytical toolset, has consequences for (a) which aspects of the gamma radiation decision-making process can potentially be democratized; (b) who gains a voice on the issue; (c) which form of democratization process is potentially facilitated. Secondly, the democratizing effects of setting the purpose of knowledge production, defining the research object and developing the methodological toolset are closely intertwined. Finally, providing space for multiple epistemologies and being attentive towards the role of material objects—the issue at hand and the methodological devices—are of crucial importance to realize the democratizing ambitions that the GammaSense project aimed to contribute towards.

Keywords: participatory knowledge production; democratic sustainability governance; participation; nuclear energy; gamma radiation; inclusive risk governance

1. Introduction

Since the 1960s, citizens have increasingly been engaging with knowledge production in order to influence and thereby democratize environmental and health-related sustainability challenges. For example, citizens have measured air quality to demand stricter regulation of traffic and industry in the city [1–3]; reformed clinical AIDS trials in line with interests and demands from AIDS patients [4]; or mapped radioactivity downfall after Fukushima to regain sovereignty over their own health [5].

Such experiments in participation initiated by civil society received substantial academic attention in a variety of fields including sustainability studies, political sciences, sociology, and science and technology studies (STS). Moreover, while it became clear that such practices can make a contribution towards sustainability transitions (for a literature review, see [6]), the precise way in which participation takes place in such projects in practice has received rather little scrutiny so far [7,8]. What does participation come to mean and be, beyond 'taking part in', when these experiments unfold? How does participation take place, by whom, and in what? More importantly, there has been little systematic analysis of the implications thereof—of what participation comes to be in practice—for such processes' potential to democratize sustainability governance processes. Considering the claim that participation is a central element of such projects' strategies to democratize the sustainability issue at hand, this research gap needs to be addressed.

In response, this paper performs a systematic analysis of a participatory project called GammaSense in the Netherlands. This project, initiated by Dutch civil society organization Waag Society, aimed to democratize gamma radiation-related decision-making through participatory knowledge production. Specifically, they aimed to enable citizens to measure gamma radiation levels.

Below, I first of all review existing literature on participatory knowledge production processes that aim to democratize environmental governance. I will then outline the analytical framework developed for this paper in order to allow for a systematic analysis of the case, which draws on theoretical work from the fields of participatory program (or policy) evaluation research and transdisciplinary sustainability research. These (intertwined) fields developed several helpful analytical toolsets to identify and analyze variations between different forms of participation, which I integrate into a framework tailored towards this paper's specific ambitions. After a description of the methodology and a brief introduction of gamma radiation politics in the Netherlands, I present the results of the systematic analysis. The paper concludes that the way in which participation takes place throughout all stages of the research process influences the potential to democratize the sustainability issue at hand, including technically complex issues related to the design of the measurement system and analytical toolset.

2. Literature Review: Participatory Knowledge Production to Democratize Sustainability Governance

2.1. Participatory Knowledge Production: A Heterogeneous Phenomenon Studied in Multiple Literatures

Participatory knowledge production takes a wide variety of shapes and forms. It may be initiated by different actors, for example by experts from scientific establishments, by civil society organizations, or by governmental organizations. Some forms of participatory knowledge production are project-based and experimental, while others are part of long-term processes [8]. The rationale for undertaking these projects is also diverse: for example, Mielke et al. (2016) distinguish between technocratic, functionalist, neoliberal-rational and democratic forms of stakeholder engagement [9].

This literature review primarily covers existing research from the field of Science and Technology Studies (STS) on participatory knowledge production, which took place with the explicit aim of democratizing a sustainability challenge and which was initiated by actors who are not part of formally recognized research institutes [10,11]. STS can be considered the core field for understanding the politics of knowledge production processes. At the same time, this paper also draws upon and contributes towards literature on transdisciplinary sustainability research and on political science literature on participatory sustainability governance. In the next two paragraphs, I briefly summarize the main insights from these fields and argue, in the third paragraph, what this paper hopes to contribute. Of course, the short reviews below are by no means meant to survey both entire fields, but rather to highlight the relationship between this paper's approach and existing insights from both fields.

Since the 1990s, the field of transdisciplinary sustainability research, and the Zürich school that emerged with Funtowicz and Ravetz' call for post-normal science [12] and Gibbons et al.'s proposal for Mode 2 research in particular [13], has been bringing together scientists and a variety of societal actors and practitioners to co-produce socially robust knowledge [14,15]. A wide variety of models and methods have been developed to facilitate such processes, and investigations of these different models and methods have focused on identifying both differences (e.g., [16,17]) and common ground between them (e.g., [18]), highlighting key complexities and challenges in undertaking such research (for reviews, see [16,19,20]), and developing solutions to these challenges. Some of these solutions are primarily hands-on and target-oriented, such as defining the improvements aimed for with a project upfront [21] and being attentive towards social power relations and the extent to which they hinder or facilitate open discussions [22]. Other solutions resonate more strongly with the field's overall affinity with constructivist schools of thought. For example, Kläy et al. [23] and many others have argued for the need to overcome the fact/value distinction in order to render science accountable to society in the context of a sustainability transformation—a line of argument that this paper also draws upon. Indeed,

reflexivity is a central concept within much transdisciplinary research, both with regard to stimulating reflection among participating actors (e.g., [24–26]), and with regard to transdisciplinary scholars reflecting on their own normativity and the extent to which different methods contribute to achieving these normative ambitions (e.g., [27–31]). At the same time, recent research has called for more in-depth and explicit conceptualizations of what reflexivity is or may be (e.g., [32]), and on the way in which the normativity that is embedded in choices made during the research process has consequences for the emergence, shaping and realization of normative goals (e.g., [33,34]). This paper responds to the former call by presenting a specific conceptualization of reflexivity through the development of a systematic analytical framework in Section 3, and to the latter call by investigating this relationship in the case of the GammaSense project.

The political science literature on participatory sustainability governance is large, and has primarily produced insights on the institutional aspects, stakeholder interaction mechanisms, power dynamics and results of different forms of governance in the context of addressing or preventing sustainability challenges (e.g., [35,36]). In the context of international relations as a subfield of political science, Bäckstrand [37] for example argued in 2003 that this field suffers from a lack of understanding with regard to the relationship between the role played by scientific expertise and democratic governance. Research that has filled this gap since 2003 draws strongly on the field of STS. It is argued, amongst others, that a balance needs to be struck between the use of scientific and participatory expertise based on the specific question and governance context at hand [37]; that the effects of participatory knowledge production depend on how the resulting knowledge is utilized and by whom [38], and that sustainability policy ambitions shape how participatory knowledge production takes place [39]. Overall, the primary emphasis of this literature is on governance processes, while this paper primarily engages with participatory knowledge production processes.

Indeed, this paper builds on both of these briefly reviewed studies with the aim of providing a relevant contribution by opening up the notion of participation *in practice* and what implications participation-in-practice has for such processes' wider normative ambitions. To start, Sections 2.2–2.5 below review literature on participatory knowledge production processes that aim to democratize sustainability challenges. An explicit investigation of the nature of participation in such processes and/or the implications thereof for the potential to democratize sustainability challenges is limited in the literature reviewed. Hence, the review does not necessarily present the main insights from existing research but rather provides an analysis of this research guided by the questions raised in the introduction of this paper.

2.2. Why Addressing Sustainability Challenges is Argued to Require More Democratic Engagement, and How Participatory Knowledge Production is Expected to Facilitate This

To start, existing research in the broader fields of sustainability science and sustainability governance has articulated various arguments as to why sustainability challenges need to be democratized, and how participatory knowledge production is expected to contribute towards this goal. The following three lines of reasoning can be distilled, based on an understanding of sustainability challenges as: (1) deeply embedded within existing structures; (2) multi-faceted; (3) large and urgent. These three lines of reasoning can be identified in the literature on both citizen-initiated participatory knowledge production as well as transdisciplinary sustainability science [6,19].

The first line of reasoning is based on the reflexive modernization perspective. It starts from the understanding that addressing sustainability challenges requires reconsideration of existing institutional, material and discursive structures [40]. Scrutinizing these structures, and discursive structures in particular, arguably requires a reflexive perspective [41]. Knowledge production by non-experts, then, is argued to facilitate and democratize such reflection because existing power structures, including the mainstream expert-based scientific establishment, would tilt towards unsustainability [42].

A second line of reasoning posits that participatory knowledge production democratizes engagement with sustainability challenges because citizens' involvement in shaping the direction of research makes sure that the resulting knowledge actually helps understand and address issues that are of concern to citizens [43]. This reasoning is underpinned by the idea that producing knowledge on topics of citizens' concern requires active citizen engagement from the start [44–46], and that sustainability challenges' *multi-faceted* nature heightens the urgency of doing so: the number of issues within and approaches towards a certain sustainability challenge is often large [6]. Producing knowledge on topics of citizens' concerns is important because this heightens citizens' awareness of sustainability challenges and empowers citizens to advocate for change [45,47]. Moreover, this is crucial to ensure making an impact because sustainability challenges are inherently socio-ecological, and hence cannot be solved without active societal engagement [48].

Third, and finally, there is the argument that sustainability challenges require democratic engagement because of their magnitude and urgency [49]—an argument that has particularly been voiced in the context of the Future Earth research programme, which advocates knowledge co-production between societal and academic actors to address global sustainability challenges. Because of their magnitude, these challenges affect a large number of people who are arguably entitled to have a say about knowledge production in order to make sure it is responsive to the needs of society [39,50]. This resonates with the first line of argument presented above. Next, sustainability challenges' urgency heightens the importance of ensuring that knowledge production makes an impact. As argued in the second line of reasoning above, this requires producing knowledge that is relevant to society in order to ensure active participation in addressing sustainability challenges.

2.3. Participatory Knowledge Production . . . on What, and according to which and Whose Standards?

Participatory sustainability knowledge production projects have been shown to produce various forms of knowledge. For example, many do "undone science" [51]: science that is absent from established research agendas because it is ignored and/or unfunded yet of concern to citizens, such as research on the environmental and health impacts of industrial pollution [11]. Others relate more explicitly to existing expert claims on a topic, and perform pro-active fact-making with holders of local, vocational and/or experiential knowledge to contest or amplify expert claims [52]. Knowledge produced in a participatory manner does not necessarily adhere to existing scientific standards and epistemic beliefs, particularly because projects may use different standards of proof and/or prefer false positives over false negatives [11,43,44,53,54].

In relation to the lines of reasoning that underpin participatory knowledge production for more democratic engagement with sustainability challenges presented in Section 2.2, it should be noted that case study research has shown that the type and topic of knowledge production often plays an important role in the way in which projects claim that their activities democratize engagement with the issue at hand. For example, participatory knowledge production may be argued to enable local stakeholders to redress mainstream science's tendency to ask questions, use methodologies and interpret data in ways that serve the interests of industry rather than marginalized populations [52,55]. The resulting knowledge may then pave the way to create novel ways of engaging with the issue at hand that better serve the interests of those affected by it.

2.4. From Knowledge to Democratization in Practice

In practice, the process of realizing projects' political ambitions is far from linear and uniform. To start, different groups of people may be involved at different stages [56], and participants' roles and identities may shift. For example, Epstein's (1996) research on participation in clinical AIDS trials has shown how a small group of citizen-activists gradually became recognized experts [4].

Furthermore, material objects play various roles in knowledge production processes with democratizing ambitions. These material objects include both the material aspects of the issue at hand [57,58] and material epistemic devices [59,60]. With regard to the latter, case studies on

emerging maker movements have shown that developing measurement tools or online platforms that are specifically tailored to communities' requirements and questions is an important prerequisite for achieving such projects' ambitions [2,61–63]: appropriate tools and platforms enable the production of relevant knowledge, and thereby render existing knowledge and policy procedures controversial [64,65].

Zooming in on the role of online platforms and maps in particular, research has shown that the design of these technologies influences what kinds of participation and democratization are rendered possible or fostered. For example, Google Maps API arguably facilitated two specific forms of citizens' participation in knowledge generation after the disaster at the Fukushima Daiichi power plant in 2011, namely data extraction and data aggregation [5]. Maps have further been shown to offer pilotage [66] and to construct specific definitions of threat and danger, for example by rendering certain aspects of an ecological geographical disaster visible and hiding others [67]. In other words, maps, platforms, measurement tools and other material epistemic devices can be understood as folds, bringing the 'inside' 'out' and the 'outside' 'in' [68]. This means that the politics that a map or tool is envisaged to influence play a role in the design of the map or tool, and that these maps and tools in turn enact politics by steering the way in which people engage with the issue at hand.

Next, political ambitions and the design and execution of these projects have been shown to mutually inform each other. Both political ambitions and knowledge production practices often change as projects unfold [1,56,69], especially (but not only) in cases where political ambitions are not always explicitly or concretely articulated from the start. Foregrounding action and doing, which often happens in an effort to afford collaborations between diverse groups with multiple goals, inevitably means that political ambitions emerge along with and from knowledge production practices [1,70].

Finally, research has shown that participatory knowledge production in itself does not automatically result in achieving these projects' ambitions to democratize sustainability governance. Some of the barriers towards achieving these ambitions can be identified within the knowledge production process. If existing scientific standards are not followed, it is important that their relevance gets challenged successfully. Otherwise, participatory knowledge production using different standards may well get dismissed by incumbent experts [2]. Next, even if the knowledge that was produced is considered valid, this may not be enough to achieve a project's ambitions. Vested interests may be strong, the existing system may be materially obdurate, and it may be difficult for communities to organize themselves in order to advocate for political change [71,72].

2.5. Implications of This Literature Review for This Study

To conclude, this review has shown that the articulation of the need to democratize the governance of sustainability challenges through participatory knowledge production stems from a characterization of sustainability challenges as embedded within existing structures, multi-faceted, and large and urgent.

Next, the participatory nature of participatory knowledge production and the political ambitions of such endeavours are intertwined throughout a non-linear process that is mediated by the issue at hand, the methods and tools used for knowledge production, the actors involved (and their beliefs and values), epistemic standards, and the existing governance situation. However, very little systematic analysis has been conducted on what participation comes to constitute through different knowledge production activities that take place throughout the process and the way in which this influences the way and extent to which sustainability governance can be democratized. This paper seeks to fill this gap, and the next section presents the systematic analytical framework that was developed to do so.

3. Analytical Framework

The analytical framework presented here is based on participatory programme (or policy) evaluation research frameworks that were merged and adapted for the specific research purpose of this paper by drawing on insights from the literature reviewed above. Participatory programme evaluation research focusses on forms of knowledge production that overlap with the case studies reviewed above [73]. This field has produced several analytical frameworks that are helpful to investigate and

characterize the participatory nature of (evaluation) knowledge production [73,74]. Combining these frameworks with insights from the previous sections resulted in an analytical framework consisting of two axes: an axis identifying five knowledge production practices and an axis identifying four dimensions of participation. In addition, the framework provides space to investigate the implications of the particular shape of participation with regard to these four dimensions in practice (for this paper: in the GammaSense case) for the democratization of the sustainability issue at hand (gamma radiation-related decision-making).

3.1. Knowledge Production Practices

To start, this framework identifies and distinguishes between different practices that are part of any knowledge production process: (a) setting the purpose, understood as the discursive practice of outlining why knowledge production is undertaken [75]; (b) defining the research object, understood as the practice of identifying the topic under investigation as well as the nature of this topic [73,75]; (c) empirical research, understood as the practice of developing the methodology (including the measurement tools that were highlighted in Section 2) and of collecting data [73,76]; (d) analysis, understood as the practice of developing the analytical framework (including the standards highlighted in Section 2) as well as analyzing and interpreting data [73]; (e) data reporting, which includes paying attention to the development of platforms and maps [73].

As highlighted in the literature review above, these practices do not necessarily take place sequentially [1,56,69]. They may overlap and take place simultaneously or at multiple moments throughout the process. However, identifying them as distinct practices allows for an investigation of the implications of what participation looked like in each of these practices for the ambition to democratize engagement with the issue at hand. The analysis below therefore distinguishes between these different practices while recognizing that they are entangled and overlap.

3.2. Dimensions of Participation in Each Knowledge Production Practice

With regard to the dimensions of participation, the framework is first of all based on Cousins and Whitmore's work, who distinguished between control, stakeholder selection and depth of participation [77]. Cousins and Whitmore's definition and operationalization of these three dimensions are refined with insights from subsequent research on participatory program evaluation as well as the literature reviewed in Section 2.

The first dimension is **control over decision-making**. Studying this dimension empirically first of all requires identifying who has (or have) the final say when making a decision. Furthermore, it also requires investigating how and why a particular (group of) actor(s) gained control over decision-making [73,75].

The second dimension is **stakeholder selection** [77]. This requires investigating who gets to participate. What kind of group do participants represent? Citizens, civil society organizations, companies, bodies of government, expert organizations? People who are directly affected by the issue? People who are affected by the potential governance implications of the knowledge that is produced [78]. How are stakeholders selected? Do stakeholders self-identify as stakeholders and take the initiative to participate, or are they selected and invited by those who initiated the process [79]?

Cousins and Whitmore's third and final dimension is **depth of participation**, for which they distinguished between consultation and deep participation [77]. For the purposes of this framework, this understanding is further refined by drawing upon Schneider and Buser's work [80]. They distinguished between three different roles: informing, consultation and co-production. Stakeholders with an informing role are informed about the steps taken during the knowledge production process and are, at most, given the opportunity to provide feedback, although this hardly influences the knowledge production process. Stakeholders with a consultation role are invited to share their view on different steps taken and planned throughout the knowledge production process, and this may lead to

adjustments in the process. Finally, stakeholders with a co-production role play an active role in shaping and executing the different parts of the knowledge production process.

In addition to the three dimensions from Cousins and Whitmore's framework, this paper's framework includes a fourth dimension: the (epistemic) **type of knowledge** produced in participatory knowledge production processes [77]. Research in the field of participatory program evaluation research has shown that this dimension can have implications for such processes' emancipatory potential [76,79,81,82]. Indeed, the literature reviewed in Section 2 also suggests that this dimension can be defined and operationalized in various ways. To do so, this paper particularly draws on program evaluation research frameworks that were developed in the context of evaluating sustainability-oriented programs, namely by Enengel et al., Kuindersma et al. and Enengel et al., to distinguish between experiential and scientific knowledge [82], which resonates with discussion on the type of knowledge produced in existing case studies of participatory knowledge production processes that aim to democratize sustainability challenges (Section 2.2). Kuindersma et al. distinguish between system-analytical, critical-theoretical and social-constructivist types of knowledge [76]. System-analytical knowledge is knowledge on whether and why certain (policy or program) objectives may or may not be reached. At most, this knowledge allows actors to be critical about the extent to which current governance ambitions, with regard to the issue at hand, are being achieved. Critical-theoretical knowledge results from questioning existing policy or programme objectives in relation to the issue at hand, and therefore resonates with the observation in Section 2.1 that sustainability challenges require participatory knowledge production because of their intertwinement with wider structures. However, this type of knowledge does not produce knowledge on the issue itself in order to generate alternative objectives. The third, social-constructivist knowledge, builds on the understanding that knowledge is not objective but the result of an active process of construction. Therefore, this type of knowledge production requires critical engagement with the political nature and value-ladenness of making choices throughout the knowledge production process [78]. Relatedly, and finally, Hage et al. argue for identifying whether the fact–value distinction is maintained or not [81]: if the fact–value distinction is not maintained and knowledge is understood to be the result of an active process of construction, this opens up space for the use of a variety of non-scientific approaches and standards [78].

3.3. Democratizing Sustainability Governance

Finally, this paper seeks to understand the implications of all of the above (how the way in which participation takes shape along each dimension and for each knowledge production practice) for the potential to **democratize sustainability governance**. Considering the nature of sustainability challenges, as discussed in Section 2.2, the first line of enquiry here is to identify **what** (which aspects) of the issue at hand citizens were or would be able to challenge based on the participatory knowledge production process and its outcome, and what citizens can and cannot say about these aspects of the issue at hand—based on the argument that different conceptual and methodological approaches to the same issue can yield different understandings thereof [83,84]. Sustainability challenges often contain a strong risk element, and the governance of gamma radiation is a clear example thereof: sustainability challenges inevitably require dealing with hazards and insecurities [85]. Therefore, besides an open-ended enquiry into which aspects of the issue at hand can be democratized, the term 'what' here also entails mapping which aspect of the risk governance process gets opened up for participation. Following Renn et al.'s (2011) inclusive risk governance framework, this paper distinguishes between pre-estimation, risk estimation, risk evaluation and risk management [86]. The second line of inquiry, acknowledging that citizens are far from a heterogeneous group, focusses on **who** gains a voice in the matter. The third line of enquiry is to identify **how** (through what kind of democratic process) the participatory knowledge production process can potentially facilitate democratization of the issue at hand. While recognizing that the role of knowledge in governance practices is contingent upon a wide variety of factors, as outlined in Section 2.4 and in various reviews on the topic (e.g., [8,87,88]), knowledge in itself can play a strong role in enabling and

disabling specific forms of democratization [69]. This paper distinguishes between three common forms of democracy, namely representative, participatory and deliberative, and direct democracy (e.g., [89]). Democratization in a representative manner entails that citizens have access to knowledge that is relevant to them in order to make more informed decisions on which politicians they elect. Democratization in a participatory and deliberative manner refers to public involvement throughout the governance process through deliberation on the issue at hand (e.g., [69,90]). Democratization in a direct manner refers to a situation in which citizens decide directly on issues rather than mediated through representation or deliberative processes [91].

3.4. Synthesis, Summarizing Table and Outlook

Importantly, this design of the framework allows for understanding the relationship between the four dimensions of participatory knowledge production on the one hand and the democratization of sustainability governance on the other hand—for each of the five knowledge production practices. The key questions that the analysis below asks of the empirical materials are: How do these each of the dimensions steer and shape how the sustainability issue at hand can be democratized? Which of these dimensions are particularly influential, and during which knowledge production practice? Which dimensions are less crucial?

Table 1 summarizes the framework. The arrow represents that the framework investigates how the first four columns inform the content of the fifth column. Next, the paper first of all outlines the methodology and basic characteristics of the case study at hand. This is followed by a systematic analysis of the case using the framework. A filled-up table and analysis of the intertwinement between participation in practice and democratizing ideals is then presented as the result. The paper ends with reflections on the framework's strengths and shortcomings, including the extent to which the different practices and dimensions of participation can be considered relevant for understanding participatory knowledge processes' normative (democratizing) ideals.

Table 1. Participatory knowledge production to democratize sustainability governance: dimensions and practices.

	Control over Decision-Making	**Stakeholder Selection**	**Depth of Participation**	**Type of Knowledge**	**Implications for the Democratization of Sustainability Governance**
Setting the purpose					
Defining the research object					
Developing the methodology & collecting data					
Developing the analytical framework & analysing and interpreting data					
Data reporting					

4. Methodology

4.1. About the Case: GammaSense

This paper is based on a case study of GammaSense, which consisted of two phases: the GammaSense project (March 2017–July 2017) and the Gammasense 2.0 project (September 2018–March 2019). GammaSense was initiated by Waag Society, which is a civil society organization that describes itself an institute for art, science and society that explores the social and cultural impact of new technologies. They aim to open up, develop and use technology for citizen empowerment based on

their key values of openness, fairness and inclusiveness [92]. The initial GammaSense project was funded by the European Union H2020 programme and involved participation by citizens, RIVM (the Dutch National Institute for Public Health and the Environment), WISE (an activist organization campaigning against nuclear energy and for renewables), and local governments of the cities of Maastricht, Eindhoven and Bergen op Zoom—cities in which controversy around nuclear power was already ongoing in 2017. GammaSense 2.0 was funded by the SIDN fund, a fund that funds innovative internet projects, and carried out in collaboration with WISE. Throughout the analysis, Waag Society is considered as the party initiating the project, while all other actors involved are participating stakeholders.

This case study was first of all selected because it clearly expressed the ambition to produce knowledge about gamma radiation as an environmental and health-related sustainability issue in order to democratize gamma radiation-related decision-making, which is central to the question this paper seeks to answer. Additionally, the case study (GammaSense and GammaSense 2.0 combined) took place over a longer period of time, and both the participatory knowledge production itself as well as the project's overall democratizing ambitions changed course several times throughout the trajectory. This allowed for an in-depth probing of the connection between the two (participation practices and democratizing ambitions), in line with the analytical ambitions of this paper. Furthermore, the project also reflected on its own practices in order to learn how participation could be done 'better', thereby allowing for highly in-depth, nuanced investigation. Finally, the empirical focus on gamma radiation, rather than themes such as air quality, noise or industrial pollution, was selected because both participatory knowledge production and research thereon are scarce on this topic outside the context of actual nuclear disasters, Fukushima and Chernobyl in particular.

4.2. Data Collection Methods

The proposed analysis requires qualitative research methods: it is necessary to uncover underlying ambitions, reasons and motivations; to study how different aspects of the framework outlined above relate to each other; and how these relationships may shift as a project unfolds [93]. I therefore combined in-depth semi-structured interviews (20) with participant observation and document analysis. All interviews were highly interactive, as we also discussed my own preliminary research findings in relation to interviewees' ideas and experiences. Of course, I carefully distinguished between interviewees' initial remarks and their expressions in reaction to my own remarks when analyzing the interview materials. Between 3 and 6 representatives were interviewed from each type of actor that participated in the project: Waag Society itself, local government representatives, scientists from RIVM (the Dutch National Institute for Public Health and Environment) which is the official authority responsible for monitoring gamma radiation levels in the Netherlands, and of course citizens.

I developed a separate protocol for each individual interview, relevant to the role played by the actors interviewed and the stage the project was in when the interview took place. During all interviews and participatory observation sessions, I took extensive notes, which were typed up immediately after the interview [94]. These notes are very detailed, and include information on the setting in which the event took place, what the actors who were present said and did—in general and in interaction with me—and my reflections thereon based on this paper's research questions. When the setting allowed for it, interviews were recorded and transcribed.

4.3. Chronological Overview: Interaction between the Use of Different Methods and Steps of Analysis

To start, I conducted interviews with the GammaSense project leader and the leader of projects that preceded and informed Gammasense (outlined below) to understand the initial design of the project and the rationale behind it. These first two interviews took place before the start of the GammaSense project.

Next, I conducted participant observation at the participatory workshops, which were organized by Waag Society between March and June 2017 in Maastricht, Eindhoven, Bergen op Zoom and

Amsterdam. This allowed for a (limited) understanding of how participatory knowledge production took place materially and in practice and provided a starting point for my investigations of different participating actors' views and discourses thereon. Based on a preliminary analysis of my notes of the first two interviews and the workshops guided by the main concepts of the analytical framework, I identified which issues required in-depth probing and set up interviews with participating actors to do so. During each interview, I focused on how the interviewee approached the project, why he/she participated, what this participation looked like in practice, what choices they made or felt should be made and what they argued the project could achieve by doing so. I also made several follow-up participant observation visits at Waag Society's office to witness how the project further unfolded, both during the initial GammaSense project and during the design phase of GammaSense 2.0.

While performing participant observation and conducting interviews, I analyzed documents that were published about both GammaSense and GammaSense 2.0 as they became available. These documents consist of the GammaSense project website, blog posts on GammaSense on the Waag Society website, and reports that Waag Society produced about the project for both the general public and the EU funding programme. None of the other actors involved produced substantial documentation. For the analysis of the initial GammaSense project and the design of GammaSense 2.0, these documents were primarily used to triangulate findings from the interviews, and at times to fill in missing information when required. For the analysis of the unfolding of GammaSense 2.0 after its design, I draw almost exclusively on document analysis and some informal interaction with Waag Society representatives.

The overall analysis, taking all gathered materials (cf. [95]) into account, took place in a step-wise manner and was partly deductive and partly inductive. First of all, I coded the materials according to the five different knowledge production practices presented in the analytical framework. Next, within the materials covering each of these practices, I identified and coded the four dimensions of participation. In addition, I used three codes to identify which aspects of gamma radiation-related decision-making played a role in each dimension of participation, what citizens were able to say about these aspects and the form of democratization (representative, participatory and deliberative, and/or direct) that was potentially enabled. By placing all coded materials side-by-side, I inductively identified the relationship between the four dimensions of participation and the democratization of gamma radiation-related decision-making and reflected on the intertwinement of the different knowledge production practices throughout the GammaSense project. As the conceptual framework was refined over the course of writing this paper, this process was repeated several times.

Table 2. lists all methodological research activities in detail.

Table 2. Research activities.

Semi-Structured Interviews	- 6 Waag Society representatives:
	  ○ The project leader of GammaSense's precursor projects
	  ○ GammaSense first project leader (2x, prior to project take-off and mid-way)
	  ○ GammaSense's second project leader
	  ○ 2 community organizers
	  ○ Software developer
	- 6 citizen-participants of participatory workshops
	- 4 local government representatives from participating municipalities
	- 3 scientists from RIVM, the Dutch National Institute for Public Health and the Environment—an expert body for monitoring gamma radiation

Table 2. *Cont.*

Participant observation	Primarily during participatory workshops which were organized by Waag Society between March and June 2017 in Maastricht, Eindhoven, Bergen op Zoom and Amsterdam (where Waag Society itself is located); several follow-up visits to participate in project development at Waag Society's headquarters.
Document analysis	All posts on the Waag Society website (www.waag.org) and GammaSense website (www.gammasense.org), and publications pertaining to this project and the wider Making Sense project as part of which the GammaSense project was initially conceived

5. Dutch Nuclear Energy Politics

To understand the GammaSense project, it is important to first understand the Dutch nuclear energy politics. Nuclear energy is a controversial issue in Dutch national energy politics, although the country has just one commercial nuclear powerplant (located in Borssele, Zeeland), which generates only 4% of the electricity produced in the Netherlands [96]. In face of this relatively small contribution of nuclear power to the current energy mix, public controversy largely centres around the role that nuclear power could play in future energy transition scenarios, Dutch nuclear waste policy, and the so-called Borssele deal [97].

With regard to the first issue, the majority of the Dutch population has not been in favour of nuclear power production to replace fossil energy sources since the Chernobyl disaster, and environmental movements mostly advocate for an energy transition based on renewables [98]. The Borssele deal—which proposes to keep Borssele open longer than originally planned, until 2033, in exchange for investments by the plant's owners in sustainable energy supplies—and the Dutch nuclear waste policy periodically meet with public protest [98,99]. Hence, at first sight and on the national level, there appears to be rather little societal concern with nuclear power, both with regard to present or future "normal" levels of gamma radiation and the potential threat of a nuclear disaster.

However, the situation is different in Dutch border regions near the Belgian nuclear power plants, particularly around the power plants in Tihange (near Maastricht) and Doel (near Bergen op Zoom). The two plants have been controversial since 2012, when investigations revealed cracks in the reactors of both plants [100]. Controversy intensified when one of Tihange's reactors caught fire and suffered an explosion in 2016, especially after subsequent investigations revealed more cracks in the reactors. This formed the basis for widespread public fear of more substantial safety problems and a potential nuclear emergency [101].

Protests have mostly been organized by the Stop Tihange movement, a heterogeneous assemblage of transnational actors from Belgium, Germany and the Netherlands, which aims to phase out all Belgian nuclear power plants, starting with the facilities in Tihange and Doel. A central concern of this movement is a lack of transparency from public authorities and plant owners about these facilities' safety issues: issues are often entirely denied, and a lot of effort is put in monitoring incidents and temporary shut-downs at these facilities as illustrated by the numerous posts on the Stop Tihange facebook page [102]. Knowledge on the state of the reactors, on incidents and shut-downs, and on the safety implications of both thus plays an important role in these regional yet transnationally connected nuclear energy politics.

6. Results

Each of the practices listed in the analytical framework are analyzed separately below. For each practice, control over decision-making, stakeholder selection, depth of participation and type of knowledge produced are investigated, as well as the extent to which the project democratizes gamma radiation-related decision-making as a sustainability challenge.

6.1. Setting the Purpose

6.1.1. Contextualising GammaSense: A Subproject of H2020 Project 'Making Sense' (2015–2020)

To understand how the GammaSense project's purpose was set, it is important to understand its wider embedding and geneology. GammaSense was initially conceived as a subproject or 'pilot' in the European H2020 project 'Making Sense' (2015–2018). The purpose of this project was defined by its initiators, Waag Society and similar partners in Spain and Kosovo: to empower citizens to engage with environmental issues based on knowledge produced with jointly developed environmental sensing toolkits. The rationale underpinning the Making Sense project, according to its initiators, was that self-generated knowledge on issues identified as relevant by citizens would motivate and empower those citizens to adjust their own behaviour in relation to the issue as well as provide political leverage to effect change at different governance levels [103]. Within this discourse, the fact–value distinction was partly maintained: citizens were supposed to produce objective truths about the issue at hand, but within the recognition that values play an important role in deciding what to produce knowledge about and how to do so. Finally, according to Waag Society's Making Sense initiator Frank Kresin, Waag Society also aimed to learn how to design and conduct projects that actually manage to achieve changes in the way citizens engage with environmental issues through participatory knowledge production.

6.1.2. Setting GammaSense's Purpose

An earlier Making Sense pilot, Urban AirQ, had taught Waag Society that self-generated knowledge on the issue at hand alone did not mobilize citizens to actually adjust their own behavior or push for change in governance. The GammaSense project was conceived to address this problem. GammaSense's initiator argued that gamma radiation at the time of a nuclear disaster is such an urgent problem that citizen-based knowledge production thereon would automatically, without any further need for community organizing, result in widespread behavioral adjustments amongst citizens. Such knowledge was geared towards enabling challenging existing decision-making in a way that can be described as direct **democratic engagement** with risk management in the context of here-and-now-exposure to high levels of gamma radiation—bypassing the existing mechanisms in place for risk governance in terms of pre-estimation, risk estimation and risk evaluation. This form of democratization foregrounds individual agency rather than collective deliberation: citizens who do not wish to blindly follow government advice would be able to draw upon their (aggregated) self-produced knowledge to make their own decisions on evacuation rather than wait for government instructions. This specific democratizing ambition was underpinned by two sets of concerns among Waag Society's representatives. The first concern was the long institutional route from an actual disaster taking place towards government deciding what to do about it. The second concern was that data produced and released by government authorities is not necessarily trustworthy. Indeed, the GammaSense project leader repeatedly stressed that he wanted people to be empowered to decide on their own individually-preferred course of action depending on their own circumstances, rather than following one-size-fits-all instructions from the government, which could be the result of national political concerns that were not in citizens' best interests.

Waag Society initially made and **controlled the decision** to produce knowledge on gamma radiation in the context of earlier failures to achieve their projects' intended democratizing effects. However, this decision was subsequently opened up for debate during participatory workshops organized in spring 2017 in three cities near nuclear facilities (Bergen op Zoom, Eindhoven and Maastricht) as well as in Amsterdam.

These participatory workshops served to refine the design of the radiation sensing system, which this paper discusses below, and to explore for what purpose citizens and other stakeholders—local governments, regional governmental bodies responsible for emergency response and crisis management, anti-nuclear energy civil society organization WISE, and RIVM—were interested in using it.

Stakeholders were selected and invited to participate by Waag Society. The host cities for the workshops were also selected and asked to participate by Waag Society. What was the **depth of participation** of these stakeholders with regard to setting the purpose?

First, RIVM representatives primarily explained the physics of gamma radiation and how this makes it a health hazard, as well as how gamma radiation can be measured. The **type of knowledge** presented by RIVM was (non-experiential and) expert knowledge, which maintained the fact–value distinction, produced using existing guidelines and standards. They also explained the institutional infrastructure through which their independent knowledge production should result in governmental action at the time of a nuclear disaster [81,82].

RIVM did not explicitly articulate their ideas with regard to the project's purpose during the workshops. During interviews, they argued that the project's purpose, for them, was primarily to produce more fine-grained data on gamma radiation levels to complement their own measurements because they lacked data on radiation levels in the areas between their measurement stations. Although they were uncomfortable with Waag Society's articulation of the project's democratizing ambitions, they did not challenge these ambitions because they felt this was not their position: **RIVM's depth of participation** with regard to setting the purpose was hence limited to consultation, at best. Instead, they aimed to help increase the quality of the data and the interpretation thereof, reinforcing their understanding of the type of knowledge they advocated for: scientific knowledge that maintained the fact–value distinction. They were particularly worried about the societal consequences of false positives, which are often preferred over false negatives in citizen-based participatory projects yet seen as a problem by professional scientists [43]. Specifically, they feared that people would panic in reaction to high measurement results that may accidentally emerge from incorrect use of the measurement system, and argued that such a situation may easily get out of control. They felt an individual citizen arousing concern based on a single false positive may be much more convincing to the public than governmental authorities stating that all measurements are within established safety limits.

Local government representatives' depth of participation was similarly limited to consultation during the workshops themselves, except in Maastricht, where the local government was very active at the time in taking action against the controversial nuclear facility in Tihange and took a more pro-active, co-productive role in participating in setting the project's purpose. Local governments each put forward different ideas about the project's purpose. In Maastricht, the city council's official standpoint was that the nuclear power plant in Tihange should be closed and citizens actively campaigned against the facility. Similar to WISE, of which representatives were only present at the participatory workshop in Bergen op Zoom, they were particularly interested in exploring how a gamma radiation measurement system could help strengthen their anti-Tihange campaigns. Bergen op Zoom was keen to act as a test region for the measurement system. They hoped that nearby municipalities, which had so far been reluctant to join Bergen op Zoom's attempts to gain a voice at the (international) table governing the nuclear facilities in Doel, would become less reluctant to do so after participating in the 'politically neutral' activity of citizen-based gamma radiation monitoring. In Eindhoven, where gamma radiation was less of an issue of societal and political concern, the local government was similarly interested in acting as a test region for the measurement system, because this resonated with the city's wider ambitions to generate more data about the city environment together with citizens in order to be able to address these problems more effectively.

Citizens who participated in these workshops also had highly diverse ideas about the purpose of the project, and their **depth of participation** can be characterized as co-production, although this co-production varied in nature between individuals and cities. It is important to note that it was first of all difficult to attract interested citizens to these workshops, and Waag Society was only really successful in doing so in Maastricht. Some citizens attending these workshops, particularly in cities other than Maastricht, were actually rather uncomfortable with the project and its purpose as a whole: they did not really think about existing nuclear facilities as something to be worried about, and thought that partaking in permanent monitoring of gamma radiation levels would insert a new source of fear

into their day-to-day lives. Others expressed that they could not really imagine what the situation would be like if nuclear disaster were to actually take place, and therefore did not know whether they would actually use an app to measure gamma radiation if it were available in such a situation. Citizens in Maastricht mostly expressed that the ability to measure gamma radiation would be particularly useful in order to put pressure on public authorities to close Tihange. They argued it could help them become "watchdogs" because they themselves had the power to detect unsafe levels of gamma radiation emerging from Tihange's nuclear facilities. Real-time continuous knowledge on gamma radiation levels would facilitate the **democratization of gamma radiation-related decision-making** with regard to the closure of existing nuclear facilities by challenging existing risk estimations based on the knowledge produced. This democratization can take place in both a direct and a participatory manner: by gaining a voice at the table throughout the decision-making procedure, though not necessarily with the aim of deliberating the issue but—for citizens involved in on-going anti-nuclear power campaigns—particularly to advocate for closure. Indeed, anti-nuclear energy organization WISE expressed very similar ideas about the purpose of the project. Hence, although they did not **control decision-making**, their **depth of participation** with regard to setting the purpose was substantial. In theory, citizens who wish to advocate for keeping these facilities open could also use the tool to 'proof' the safety of these facilities, if the measurement results allowed for doing so, but their voices were absent throughout the entire process.

This diversity of project purposes as articulated by different participating actors remained visible over the course of the GammaSense project up to now, while enabling citizens to challenge authorities' measurements continued to be a common denominator. As the remainder of this analysis shows, the project unfolded in such a way that various purposes could be served at the same time. Hence, no single party really **controlled detailed decision-making with regard to** the purpose of the project. This created space for **stakeholders who were invited** by Waag Society to participate in **democratizing multiple aspects of gamma radiation-related decision-making**, both in a direct and in a participatory manner—namely at the time of a disaster (direct, and with regard to risk management) and to advocate for closure of controversial powerplants (participatory with direct undertones as argued above, and with regard to risk estimation). At the same time, **those who were not invited** to participate had no voice in the matter, and the focus on gamma radiation-related decision-making (and not any other sustainability issue) was a **decision that was controlled by Waag Society** (and of course project funders). As a consequence, **democratization** in a representative manner was excluded from the project entirely.

Finally, the analysis below shows that final decisions with regard to the purpose of the project were taken along with decisions on the research object, methodology and analysis. Each of these decisions had profound implications for the purposes that could and could not be achieved, and therefore the democratization of sustainability governance. Understanding the interwinement between the different knowledge production practices is therefore crucial and will be reflected upon in the conclusions.

6.2. Defining the Research Object

The research object of the project was nuclear radiation. Although citizens, municipal authorities and RIVM expressed doubts about the desirability and usefulness of measuring and interpreting nuclear radiation levels, this definition of the research object was **controlled by** and unnegotiable for Waag Society once the GammaSense project started. However, when Waag Society designed GammaSense, the choice to focus on this topic was debated within the Making Sense project team at Waag Society. The debate revolved around the question of whether gamma radiation was an issue of public concern in the Netherlands, and if this was the case, whether that concern was of such a nature that citizens would be interested in measuring gamma radiation as a means to address this concern. This debate was spurred by the fact that the Making Sense pilots were not about developing an environmental sensing toolkit behind doors and making these available once a disaster takes place, but about developing environmental sensing toolkits in a participatory manner because this was

believed to contribute to more participation overall. As the Making Sense project leader explained in an interview: the toolkits would better meet citizens' needs and interests, and the process would enhance people's engagement with the issue. Therefore, the GammaSense project only started after Waag Society had gauged the interest of WISE, RIVM and local governments—**stakeholders selected** and invited by Waag Society, representing both knowledge users and those affected by the potential governance implications of citizens measuring gamma radiation. Their **depth of participation**, so far, took the shape of consultation.

While designing the measurement system, which is described below, it became clear that different measurement systems are able to detect different levels of radiation. Because choices had to be made with regard to which measurement they were going to develop, this necessitated further delineation of the research object.

The camera of a mobile phone, laptop or tablet—a technology that almost anyone has immediate access to, and can therefore use instantly if needed—can be used to measure gamma radiation levels, but only when these levels are high: at the time of a disaster in close proximity (RIVM estimated this to be +/− 50−100 kms, depending on wind speed and direction). Detecting lower fluctuations in radiation levels, caused by much more minor incidents at a nuclear facility or at longer distance, required the use of different technologies, such as Geiger–Müller tubes, that not many people own.

Both of these options represent strong intertwinement between different research objects, purposes (as described above) and methodologies (as described below). Consequently, choices with regard to the exact research object—high gamma radiation levels associated with nearby nuclear disaster or more subtle fluctuations in lower levels of gamma radiation—had consequences for choices made with regard to the project's purpose and methodologies and vice versa. The purpose, as discussed above, remained relatively open-ended throughout the project, and the methodological toolset was therefore developed with the intention of being able to measure both low and high levels of nuclear radiation.

On the one hand, the selection of the overall research object—gamma radiation—was fully **controlled** by Waag Society, but informed by consultation with invited **stakeholders**, which included both knowledge users and those who are affected by the potential governance implications of the knowledge that was envisioned to be produced. More detailed delineation of the research object was strongly informed by the purpose envisioned by the project and reflected a social-constructivist **approach to knowledge** that built on the intertwinement of societal concerns and methodological constraints and Waag Society's normative ambition towards democratizing gamma radiation-related decision-making in both a direct manner (citizens can make their own decision on evacuation at the time of a disaster) and deliberative manner (citizens gain a say in the design of governance mechanisms to deal with high gamma radiation levels and on the governance and closure of controversial nuclear facilities). By delineating the research object in such a broad way and driven by the project's diverse purposes, the project potentially enabled interested citizens **to democratize gamma radiation-related decision-making** both with regard to risk management in the context of high levels at the time of a disaster and with regard to risk estimation in the context of deciding on the closure of controversial facilities in a predominantly direct manner with elements of participatory democracy, as detailed in the previous section.

6.3. Developing the Methodology & Collecting Data

At the start of the project, Waag Society developed a rough prototype of a measurement device, which consisted of a mobile phone, tablet or laptop camera as sensor and the device's hardware and internet connection to process and share the measurement data with a central online platform, which would analyze the data. As discussed earlier, participatory workshops were organized in Bergen op Zoom, Eindhoven, Maastricht and Amsterdam. For these workshops, Waag Society selected and invited **groups of stakeholders** to join: citizens (+/− 50 attended these workshops in total, including students participating in the context of a course assignment), local municipalities, RIVM, WISE and regional governmental bodies responsible for emergency response and crisis management ("veiligheidsregio's").

The latter only participated to share their knowledge on the existing emergency response governance system. The other stakeholders were asked for their views on why they would like to measure gamma radiation, and what design would make this system easy to use. Based thereon, Waag Society aimed to further develop this system in order to make sure the system would actually be used by citizens and other stakeholders (RIVM, local governments) potentially affected by gamma radiation and its governance.

In practice, the initial **depth of stakeholder participation** in the development of the measurement device can be characterized as consultation, and Waag Society **controlled decision-making**. Mostly, Waag Society's technology developers listened to stakeholders' views and incorporated those aspects of those views that they thought improved the system's overall quality. They also visited the RIVM to use their testing facilities and discuss their system with experts from RIVM—which Waag Society then used to increase the system's quality but in a way that was in line with the project's overall purpose. For example, RIVM advocated for calibrating mobile device cameras or using calibrated sensors that were cheaply available from the internet in order to increase the reliability of the data produced by the system. Waag Society's technology developers resisted this, arguing that aggregating a large amount of gamma radiation measurement data would be sufficiently reliable, and that it was of crucial importance that citizens would be able to start measuring gamma radiation with something directly available in their homes at the time of a disaster (which would be hampered by RIVM's wish for calibration). Waag Society representatives also discussed the possibility of calibration with participants at the participatory workshops organized in 2017.

However, participants—except RIVM representatives attending these workshops—mostly responded that they could not judge this issue, because they said they could not estimate the loss of data reliability when calibration was not performed. Later participatory workshops, organized in 2018 to develop the sensor kit discussed in the next paragraph, therefore also revolved much more around facilitating learning about gamma radiation, its measurement and its health effects, in order to increase citizens' knowledge on the topic.

When it became clear from conversations with RIVM that the measurement system based on the use of cameras as sensors could not be used to measure low levels of gamma radiation, **depth of stakeholder participation** increased from consultation to co-production. Activists from WISE and citizens in Maastricht, as well as local governments in Maastricht and Bergen op Zoom, were particularly vocal about the fact that they wanted to be able to produce knowledge about the extent to which the nuclear facilities they were worried about posed a threat to health as a result of (both short- and long-term) exposure to low levels of gamma radiation originating from these facilities. As a result, GammaSense 2.0 was set up together with WISE, and Waag Society developed the GammaSense sensorkit, a measurement device that was more sensitive, based on Geiger–Müller tubes: the technology that best balanced the need for a cheap and sensitive technology according to Waag Society.

To collect data, several of these sensorkits were handed out to interested participants in November 2019: **stakeholder selection** focused of a limited group of citizen-activists who reacted to an open invitation from Waag Society to participate. **Depth of participation** was in-between consultation and co-production: participants had to actively assemble these kits—consisting of a Geiger–Müller tube, a measuring kit and a plastic enclosure—place them in their homes and monitor them. Of course, the actual act of collecting data is performed by the sensorkit, not by the participant. At the time of writing, in May 2020, the majority of these sensor kits were not producing any data [104].

This process of developing and using the sensorkit to collect data was underpinned by multiple understandings of the **type of knowledge** that was being produced within Waag Society. On the one hand, there was a strong recognition of the intertwinement of facts and values: easy accessibility trumped (increased) reliability during the early stages, and the ambition to democratize gamma radiation-related decision-making in a participatory manner resulted in substantial design changes of the system in order to produce knowledge that was considered helpful to reach this goal. At the same time, Waag Society regularly referred to the RIVM as a source of validation for their work, reflecting an

ambition to produce scientifically validated knowledge. For example, they wrote the following text about the use of mobile device cameras as sensors to measure gamma radiation in a blog post on their website: "RIVM (one of our partners) demonstrated that this approach really works" [105].

Overall, citizens' preference to measure low levels of gamma radiation on a continuous basis was combined with RIVM's and Waag Society's understandings of the reliability of measurements produced by different kinds of sensors, and resulted in Waag Society's decision to develop a sensor kit based on a sensitive Geiger–Müller sensor rather than a sensor kit based on mobile device cameras with much lower sensitivity. As a result, WISE's and participating citizens' abilities to produce knowledge that was relevant to their wider political ambitions with regard to **democratizing gamma radiation-related decision-making** was enhanced: although citizens did not control this process, their input was taken seriously, in line with Waag Society's normative ambition that this project should produce knowledge on gamma radiation that supports citizens to gain a voice at the table with regard to gamma radiation-related decision-making to advocate for full closure of controversial facilities based on their alternative risk estimations. Indeed, knowledge produced with a monitoring device that is sufficiently sensitive to detect fluctuations in low levels of gamma radiation potentially facilitates democratization in the form of a combination of direct (because of the wish to advocate for closure, rather than deliberate on a mid-way option) and participatory (because citizens could use this knowledge to gain a stronger voice at the table in the process of deciding whether or not a facility remains open) manners. This design choice did limit the **democratizing** potential by only empowering those citizens who are concerned with gamma radiation to the extent that they are keen to obtain a measurement device and start measuring radiation levels themselves. This also makes the system less widespread and hence less suitable for use at the time of a nuclear disaster. At the same time, most measurement kits that were installed are currently not producing data, a topic which requires further investigation in the future: this of course seriously hampers the project's contribution towards more democratic gamma radiation-related decision-making.

6.4. Developing the Analytical Framework, Analyzing and Interpreting data and Reporting the Data

Data analysis and reporting the data can hardly be separated in the case of the GammaSense project: the data is analyzed through an algorithm that represents the resulting output on an online map. They are therefore discussed in conjunction.

Measuring gamma radiation with a mobile device camera as sensor required algorithms that could aggregate large amounts of data produced by numerous (thousands and more) mobile device cameras to produce knowledge on radiation levels: the output of a single camera as sensor can differ multiple orders of magnitude from the level of gamma radiation that would be measured at the same time and location with a well-calibrated Geiger–Müller tube. During the initial GammaSense pilot in 2017, Waag Society therefore worked on and **controlled decision-making** with respect to the development of such an algorithm, in open-source format. **Stakeholder selection** for participation therein was limited to inviting RIVM to discuss choices that had to be made, and their **depth of participation** was limited to consultation. These algorithm-related choices were not discussed with citizens or other participants who were invited to the participatory workshops. Most of this development process was therefore hidden from view to most participants, who expressed that this aspect or **type of knowledge** production was very difficult for them to understand. The subsequent measurement device, based on a Geiger–Müller tube as sensor, did not require such an algorithm: the data produced by the sensor was in itself considered sufficiently precise by Waag Society and a range of experts including RIVM and wider scientific consensus about the precision of Geiger–Müller tube-based measurements.

However, this data is rather unintelligible to the average citizen: what does a measurement value of 20 counts per minute (CPM) mean? What radiation levels are dangerous, in which circumstances, and to whom? In other words, citizens either had to learn how to interpret radiation measurements, or the measurement results had to be translated into something citizens were able to understand. Only then would citizens be able to judge the (un)safety of a situation and use the measurement data to

influence gamma radiation-related decision-making by official authorities or to take their own decision on evacuation if a disaster takes place. Waag Society **controlled the decision** to mostly on translating measurement data into something all citizens can understand, and felt this was a crucial component of the system throughout the project: only then would the data be actionable in the sense that citizens could use it to further their own interests with regard to gamma radiation-related decision-making.

To address this challenge, Waag Society decided to represent measurement data in traffic-light colours on an online map: measurements are green if they stay below all safety limits, orange when some thresholds were exceeded and red if serious health effects could be expected. The resulting map was designed with the intention to render it easy to understand, in line with the ambition to create knowledge that enables any citizen to take action. However, such a map provides little room for interpretation, almost prescribing citizens the best course of action. Indeed, earlier research has shown that the way in which data is represented inevitably provides specific pilotage, and that the amount of interpretation that is done before data is represented on the map increases the strength or magnitude of this pilotage [5,66]. To remedy this, the algorithms underlying this map are open source, but these are barely understandable for most citizens [104].

Interestingly, while Waag Society did **select stakeholder** RIVM to contribute their expertise on safety thresholds to develop the algorithms behind the map—limiting RIVM's **depth of participation** to consultation—, they rarely **selected and invited other stakeholders** for their input on this issue.

RIVM, in turn, argued that colour-coding radiation levels was not a value-laden question at all: they have a pre-defined table which stipulates which measurement results call for evacuation, hiding, taking jodium tablets and other kinds of actions. At the same time, they stressed that interpreting gamma radiation data is complex and requires specialist expertise. For example, the danger of high radiation levels is also dependent on the amount of time a person is exposed to them, on individual characteristics of this person such as age, and weather conditions: it may be preferable to go into hiding rather than leave your home when high radiation levels are caused by a cloud that is expected to move away quickly.

Safety thresholds were hardly discussed with the other stakeholders involved. During the participatory workshop in Maastricht, at the start of the project in 2017, Waag Society invited citizens to talk about how much of an increased chance of getting cancer would be unacceptable and therefore considered dangerous. The discussions that unfolded on the basis of this question largely revolved around the difficulty of answering this question: citizens felt unsure what it means when the chances of getting cancer increase by a certain percentage.

This process thus largely aimed to produce a scientific, non-experiential **type of knowledge** based on a distinction between facts and values. However, research on participatory knowledge production after the Fukushima and Chernobyl disasters shows that when citizens really delve into the topic, they can have very different, well-argued and legitimate views on what constitutes a sensible safety threshold for gamma radiation (e.g., [61,106]). In the case of GammaSense, the limited number of stakeholders participating in-depth (except RIVM) in developing the analytical toolset as well as the scientific approach to knowledge that upheld the fact–value distinction jointly influenced which aspects of gamma radiation **could** (**not**) **be democratized**: citizens and other stakeholders barely had a say in what safety and risk constituted and therefore how it should be governed according to them. Hence, while risk evaluation could have become more democratic through the development of alternative analytical approaches, this did not take place. This shows that the ambition to stimulate both direct and participatory democracy by enabling citizens to make their own knowledge-based decisions got compromised by the ambition to ensure that the knowledge that is produced is accessible and understandable, mediated by strong reliance on experts and the epistemic frames put forward by RIVM. At the same time, presenting data in a highly processed, accessible manner enabled participating citizens (both producing and using the data) to gain a voice on gamma radiation without having to make a substantial effort to understand the data.

7. Conclusions & Discussion

This paper investigated the GammaSense project as a case of participatory knowledge production with the ambition to democratize the governance of a sustainability challenge—in this case, gamma radiation-related decision-making. The overall results are summarized in Table 3, which brings to the fore how the way in which participation takes place in practice shapes what aspect of the issue at hand can potentially be democratized, by whom and how. To do so, the paper first of all developed a framework for systematic analysis, primarily drawing upon participatory program evaluation research (e.g., [73,76–78,107]). Next, the GammaSense project was analyzed through the lens of this framework. This conclusion and discussion section first of all presents the paper's key insights, reflects on the strengths and shortcomings of the framework and presents key avenues for future research.

7.1. Key Insights: Participatory Knowledge Production for More Democratic Sustainability Governance?

This paper clearly illustrates that the way in which participation takes place in practice, throughout all parts of the knowledge production process, has profound implications for what *democratization* comes to mean: in terms of what aspects of a sustainability governance challenge can get democratized, by whom and how. Based on this understanding, this section presents three key observations that are helpful for both academic research seeking to understand this relationship and practitioners looking to engage with participatory knowledge production in such a way that it results in the specific democratization of sustainability governance they seek to facilitate. The insights presented here may therefore not only be relevant to STS scholars seeking to analyze and understand citizen-based knowledge production initiatives, but also to transdisciplinary sustainability research (in particular, in response to calls to understand the relationship between normativity that is inherent to knowledge production on the one hand, and the production and realization of normative goals on the other hand) and to participatory program evaluation (as explicated more in-depth in Section 7.2 below). Considering this three-fold contribution, this paper also underlines and responds to Pettibone et al.'s (2018) plea for an intensified conversation between citizen science and transdisciplinary research: both forms of participatory knowledge production have extensive expertise on key issues of concern in both fields, with regard to stakeholder engagement, knowledge production and sharing, and the role of normativity and reflection thereon [108]. Finally, this section ends with a brief reflection on the extent to which these observations pertain to *sustainability* challenges in particular.

First of all, the analysis brings to the fore that the democratization consequences of the way in which the three practices of "setting the purpose", "defining the research object" and "developing the methodology & collecting data" took place were closely intertwined in the GammaSense case. Choices with regard to each of these three aspects clearly affect each other, mediated by the material characteristics of the issue as well as of the measurement device developed [58,60]. In the case of GammaSense, it was particularly visible that choices with regard to the sensor used (digital device cameras or Geiger–Müller tubes) played a major role in delineating the research object, restricting who could take part in more democratic gamma radiation-related decision-making through participatory knowledge production (all digital device owners vs. those who own a Geiger–Müller tube and measurement kit), and delineating which aspects of gamma radiation-related decision-making could be democratized (only emergency response at the time of a nuclear disaster, or the governance of controversial nuclear facilities as well). Hence, choices made during each of these three practices within a knowledge production process influence the democratization of gamma radiation-related decision-making in both direct and indirect manners. This means that it is of crucial importance to be attentive towards this intertwinement when making these choices.

Table 3. Results.

	Control over Decision-Making	Stakeholder Selection	Depth of Participation	Type of Knowledge	Democratizing Sustainability Governance
Setting the purpose	Overall purpose-setting was controlled by Waag Society; stakeholders interested in challenging existing gamma radiation-related decision-making structures could set a more detailed purpose	Upon invitation; both knowledge users and those affected by the governance implications of the produced knowledge; formally recognized experts (RIVM)	Mostly co-production, except RIVM, who were consulted.	Recognizing fact–value intertwinement, but producing objective truth	What: how to respond to here-and-now exposure to high levels (risk management); and whether or not existing nuclear facilities remain open (risk estimation and risk management). Who: citizens unwilling to blindly follow government emergency response advice; citizens advocating for closure of nuclear facilities. How: predominantly direct and some participatory democratization
Defining the research object	Followed from decisions on purpose and methodological toolset, controlled by Waag Society	Upon invitation; both knowledge users and those affected by the governance implications of the produced knowledge; formally recognized experts (RIVM)	Consultation	Did not play a role at first, but a recognition of the fact–value distinction when the research object was defined in more detail helped steer choices towards decisions that reflected stakeholders' interests	What: see above. Who: interested citizens. How: see above
Developing the methodology & collecting data	Controlled by Waag Society	Upon invitation; knowledge users and those affected by the governance implications of the produced knowledge; formally recognized experts (RIVM)	Informing/limited consultation in the case of citizens and local governments; consultation/co-production in the case of civil society (WISE); consultation in the case of RIVM	Recognizing fact–value intertwinement, but producing objective truth	What: whether or not existing nuclear facilities remain open (risk estimation and risk management). Who: citizens who are concerned to the extent that they are willing to obtain and use a measurement device (including WISE activists). How: mixture of direct and participatory democratization
Developing the analytical framework; analysing and interpreting data; data reporting	Controlled by Waag Society	Upon invitation; knowledge users and those affected by the governance implications of the produced knowledge; predominantly formally recognized experts (RIVM) invited	Consultation with RIVM; attempts at consultation with citizens, local governments and WISE.	Predominantly scientific; fact–value distinction largely maintained	What: how to respond to here-and-now exposure to high levels, and whether or not existing nuclear facilities remain open. Crucially: not on what constitutes an acceptable health risk, and hence risk evaluation was not democratized. Who: all interested citizens regardless of effort or background. How: see above

Secondly, decision-making was controlled by Waag Society throughout the project; participation took place based on Waag Society's invitation, and the depth of participation was (mostly, except with regard to setting the purpose) consultation at best. Although one may expect that this severely limits the extent to which the sustainability governance challenge at hand could be democratized, this was not the case: when decisions were taken on the basis of a recognition of the intertwinement of facts and values (following Kläy et al.'s suggestion [23]), the invited stakeholders' input—and that of citizens and WISE in particular—was taken very seriously. As a result, the process resulted in a methodological toolset capable of measuring those aspects of gamma radiation that selected participants who were invited to raise their voices (citizens and WISE, and to some extent the local municipality of Maastricht) were mostly concerned with. This, in turn, enabled these actors to potentially strengthen their voices in a direct and participatory—not representative—democratic manner on their issue of concern. Indeed, the choices made through each of the knowledge production practices analyzed were all geared towards fostering direct and participatory democracy: real-time knowledge of gamma radiation levels is not helpful to make a more informed decision when selecting a political leader in the context of a representative democracy.

Thirdly, the design of the analytical framework and reporting format relied almost exclusively on formally recognized expert knowledge and a rather strict separation of facts and values, and underestimated the extent to which maps and other forms of data representation provide specific pilotage. Consequently, there was no debate about the meaning of 'risk' and what levels and forms of risk are (un)acceptable to whom and how this should be represented in order to maximize people's ability to take their own decisions—questions that are central to risk evaluation, which indeed remained at the background throughout the project (cf. [86]). Hence, this lack of debate constituted a political closure that resulted from the way in which participation and knowing were configured [50,109]. Consequently, the ambition expressed by Waag Society at the outset of the project, namely to democratize gamma radiation-related decision-making in such a way that citizens also have the space to define what they are concerned with and which aspect of gamma radiation-related decision-making they would like to challenge, got compromised. This observation strongly underlines the importance of providing space for epistemic diversity in stimulating democratization through participatory knowledge production (e.g., [69,110]). Participation in itself is hence not a guarantor for facilitating more democratic sustainability governance, but specifically requires the creation of an epistemic space in which non-scientist participants are taken seriously as producers of valid knowledge, and to discuss the way in which knowledge representation steers people's thoughts and behavior.

How do these observations relate to *sustainability* challenges and their democratization? Literature reviewed in Section 2.2 suggests that arguments for democratizing sustainability challenges through participatory knowledge production are based on three characteristics of sustainability challenges: (1) their embedding in existing structures that are difficult to recognize for incumbent actors [40–42]; (2) their multi-faceted and socio-technical nature [43–48]; (3) their magnitude and urgency [39,49,50]. The GammaSense case has shown that recognizing intertwinement of facts and values, as suggested by Kläy et al. [23], is particularly important in the context of the first and second line of reasoning. Namely, without this recognition, it is difficult to challenge discursive structures such as definitions of 'risk', and the analysis has also shown that recognizing this intertwinement was of crucial importance to identify which precise aspect of (multi-faceted, socio-technical) gamma radiation-related decision-making was considered to be most in need of democratization among stakeholders and to understand the implications thereof of how knowledge should be produced (with which methods). With regard to sustainability challenges as large and urgent, the case has shown that this substantially complicates stakeholder selection: a wide variety of actors are affected by the issue at hand. Waag Society invited various different stakeholders to participate, but managed the debate and subsequent decision-making in such a way that the interests of citizens and civil society organizations who were actively concerned with gamma radiation-related decision-making were already prioritized. This, of course, excluded the

perspectives of others such as citizens who voiced concerns with the potential increase in fear and societal unrest around gamma radiation through such conscious, active engagement with the issue.

To end, with regard to rendering risk governance more inclusive, the analysis has shown that participatory knowledge production that provides new knowledge that is complementary to or challenges existing knowledge can be used to challenge existing risk estimations (cf. [86]). Doing so in a way that knowledge is directly available to citizens to inform their own decision-making, as GammaSense aimed to do in the case of a nuclear emergency, can bypass the entire existing risk governance system and directly democratize risk management. However, failing to open up discussions about what constitutes acceptable levels of risk, to whom, and why, means that the risk evaluations were not democratized. Finally, affecting risk pre-estimation was not part of this project at all. Although the very act of putting a permanent monitoring system in place around controversial activities of course has the potential of spurring wider public debate around the issue, thereby placing gamma radiation more firmly on the public agenda, this was hardly discussed nor featured throughout the project in practice.

7.2. Strengths and Shortcomings of the Framework and Its Key Concepts

The analytical framework developed for this paper was helpful to make these observations. It helped to understand participation in practice in a multi-faceted manner that is both oriented towards actual practice as well as towards the epistemological and discursive underpinnings of those practices. Crucially, it facilitated an analysis of the way in which normative objectives are set and achieved in relation to choices made throughout the knowledge production process. As such, it also constitutes a valuable contribution to the field of participatory program evaluation, based on which the framework was primarily developed. It may also be relevant to transdisciplinary sustainability research, as a helpful tool to respond to recent calls for research on the way in which the normativity that is embedded in choices made during the research process has consequences for the extent to which normative goals are achieved (e.g., [33,34]).

At the same time, there is of course room for improvement. First of all, the framework could be developed further through future research that develops theory on the relationships between different aspects of the knowledge production process, rather than presenting these aspects of the knowledge production process as separate parts of the same practice. Developing the framework in this direction would do more justice to the inherently non-linear and intertwined character of these processes [1,56,69]. Including the mediating role played by both the material characteristics of the issue at hand and of the measurement devices deployed in intertwining different aspects of the knowledge production process may be a fruitful first avenue [5,57,58,67,84].

With regard to the specific concepts deployed in the framework, the distinction between analysis and data reporting requires further theoretical refinement in the context of digital technologies (such as online platforms, in the case of GammaSense) that often conflate analysis and data reporting. This paper dealt with this conflation by analyzing both practices at once, but future research could benefit from understanding the difference between both practices even when they are closely interconnected through technology. Secondly, in its current conceptualization, the column of 'control over decision-making' was not always relevant in the analysis. Control over decision-making was almost solely in the hands of Waag Society—throughout the entire project. However, this discounts the role played by a variety of actors in steering these decisions (e.g., funders, or through the need for attracting citizens' interests in order to get them to participate). A more nuanced understanding of power-relationships that help understand the way in which decisions are taken would therefore be helpful, and Rosendahl et al.'s [22] usage of the notion of 'strong objectivity' in the field of transdisciplinary research would be a fruitful starting point.

7.3. Key Avenues for Future Research

Improving this framework (Section 7.2) and deepening the identified relationships between participatory knowledge production and democratizing sustainability governance (Section 7.1) requires applying this framework in a much wider set of cases. Indeed, this paper only constituted a first attempt at a systematic analysis of the relationship between participatory knowledge production and the democratization of sustainability governance in practice. Future work should apply this framework to a diverse set of cases, including cases in which the produced knowledge was actually used to challenge existing sustainability governance mechanisms in practice—something which did not happen in the GammaSense case (yet). It should also investigate whether the development of the analytical toolset and the epistemological underpinnings thereof is equally crucial in other cases. Another question to be further explored is: do the research results differ for cases in which the aim was *not* to challenge and confront existing expert knowledge, as GammaSense aimed to do [52], but to do 'undone science' (knowledge production on an issue that simply hasn't received attention because it has no political and economic priority at the moment [11])? Moreover, what observations in this paper pertain to the issue of gamma radiation in particular and not to other sustainability challenges? For example, gamma radiation is a highly intangible and complex issue, compared to for example air quality or industrial water pollution, and this may have its bearings on the way in which participatory knowledge production takes place in practice. Additionally, more research is needed on the relationship between the above-mentioned observations and barriers to making an actual impact on the sustainability issue at hand that have already been identified in the literature. This, for example, includes the difficulty of getting knowledge to be taken seriously if it is produced using different standards than those accepted by experts [2] or the importance of communities to organize themselves throughout the process of producing and using knowledge to challenge the issue they are concerned with [71,72]. Such research would very much benefit from a more in-depth engagement with political science literature on participatory sustainability governance, in which the governance-process, rather than the process of knowledge production, is the central object of analysis (e.g., [37,38]). At the same time, and finally, considering that this paper has shown that the way in which participation takes place during these processes has implications for the (in)visibilities that are produced and hence for the (in)actionabilities for governance that are thereby created, future research in this field would benefit from a stronger focus on the role of participatory knowledge, not as something that is objective but as something that is emergent and context-bound, in governance processes.

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