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Implementing responsible research and innovation and sustainability assessment in research projects: A framework and application

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ABSTRACT

Responsible research and innovation concepts are popular at higher levels of organising research policy, which must align with the design and management of individual research projects. However, at this lower level, there is still a need for clearer guidance on how to support responsible research and innovation through the development of socially desirable and sustainable technologies. This is particularly evident in the agri-food sector, where calls for innovation have been on the increase, but novel technologies are often controversial and their contribution to sustainable development is uncertain. Integration of responsible research and innovation with sustainability assessment is required at the early stages of technology development in projects, during which technology development can still respond to social concerns and sustainability assessments. The few first attempts are often vague about the methods applicable in projects to support the sustainable and responsible development of technology. This paper develops a conceptual approach that integrates methods required to support the anticipation, reflexivity, inclusion, and responsiveness keys of responsible research and innovation with sustainability assessment methods, along typical phases of a research project. A case study of agricultural photovoltaics illustrates the applicability of the framework across a full research project cycle. The framework addresses the gap in how to apply methods that support responsible research and innovation and sustainability assessment in research projects. It enables synergies between responsible research and innovation and sustainability assessment. In the first steps of assessment, when the unknowns and uncertainties surrounding novel technologies are great, research and sustainability assessment require systematic anticipation of developments and impacts. In this context, sustainability assessment can support reflexivity in more detail than previously suggested approaches.

1. Introduction

Research and innovation are key in transitions towards more sustainable development and part of the required transformation of socio-technical systems (Fagerberg, 2018; Schot and Edward Steinmueller, 2018; Geels, 2019). However, the extent to which the innovations targeted and the underlying research will be socially desirable and contribute to sustainable development is often unclear (Janssen, 2019; Haddad et al., 2022; Eckerberg et al., 2023; Giuliani, 2018; Janssen et al., 2022). For example, agriculture and related land use contributed about 17 % to global anthropogenic greenhouse gas emissions in 2018 (FAO, 2020), while the agri-food sector itself suffers from climate change (Wheeler and von Braun, 2013; Arora, 2019; Wiebe et al., 2015). Similarly, agriculture both contributes to and suffers from soil erosion and biodiversity loss (Borrelli et al., 2017; Ortiz et al., 2021; Pe'er et al., 2014). Innovations in the agri-food sector are therefore necessary. However, sustainability outcomes of research and innovations in the agri-food sector are mixed and hotly debated, because of complex social, economic, and ecological entanglements of farming and increased public and academic concerns about the sustainability of currently dominating models of the agri-food sector (e.g. Gremmen et al., 2019; Pe'er et al., 2020; Gawith and Hodge, 2019; Dawkins, 2023). These involve disputed technologies, such as genetically modified organisms, pesticides, cellular agriculture, or nanotechnology.

Due to the intensifying problems of the agri-food sector and the need to sustain food supply and maintain viable rural communities, there is a

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need for transformative research and innovation to increase the sustainability of the agri-food system, and respective efforts have been made (e.g. Klerkx and Begemann, 2020; Klerkx and Rose, 2020; Eckerberg et al., 2023). Responsible research and innovation (RRI) aims to address such issues through research and innovation policy and practice that is reflexive and responsive to social demands and concerns (e.g. Schomberg, 2019; Stilgoe et al., 2013; Owen et al., 2021b; Wiarda et al., 2021). RRI further aims to steer future technologies towards social desirability and sustainability at early stages, when technologies are still being developed (Pansera et al., 2020; Macnaghten, 2019; Matthews et al., 2019). Approaches such as anticipatory governance (Guston, 2014), mid-stream modulation (Fisher et al., 2006; Schuurbiers, 2011), real-time technology assessment (Guston and Sarewitz, 2002), or constructive technology assessment (Schot and Rip, 1997) are traditionally seen to support RRI in this respect, although without a direct focus on the management of research projects. RRI requires the involvement of the various stakeholders directly or indirectly affected by research and innovation, which is central to responsible implementation of research and technology development projects, because it promises to support socially desirable and acceptable innovation (Chilvers and Kearnes, 2020; Scheufele et al., 2021; Kaplan et al., 2021).

In the same vein, sustainability assessment (SA) provides information for research and innovation projects by jointly estimating the social, environmental, and economic impacts of novel technologies or systems, for example, as part of recently proposed constructive SA (Matthews et al., 2019). Applying SA in the early stages of developing a technology can thus guide decisions on further development towards more sustainable designs. The literature on environmental SA for novel technologies is growing rapidly (Thonemann et al., 2020). Data availability, quality, scaling, comparability of the studies, and the uncertainty of results are the main challenges of conducting future-oriented environmental SA such as prospective life cycle analysis (LCA). Economic SA has also been used to assess the potential of emerging technologies, with guidelines being developed (Thomassen et al., 2019; Zimmermann et al., 2018). Examples of social SA applied in the early development stages of a technology are much more limited (Haaster et al., 2017). However, the challenges identified for environmental SA also apply to social and economic SA. Scenario modelling, defining ranges of system configurations, and high-quality primary data gathering—ideally with strong stakeholder engagement—can help address these challenges (e.g. Bruhn et al., 2023; Langkau et al., 2023; Thonemann et al., 2020).

There are still gaps in the application and integration of RRI and SA approaches in research projects. Although RRI is attentive to social desirability at higher levels of organising research policy and funding, it still struggles to address academic practice in terms of the design and management of research organisations and their individual projects (Owen et al., 2021a, 2021b; Pansera et al., 2020; Espig et al., 2022; Glerup et al., 2017; Hove and Wickson, 2017; Ribeiro et al., 2017). RRI should affect practice in projects; however, researchers could simply formalise and outsource RRI if they cannot make sense of it in their work (Felt, 2017). There are examples of engaging the public and researchers in anticipatory and reflexive activities within research projects, including national research councils' efforts to encourage the application of RRI keys in projects (Pansera et al., 2020; Taylor et al., 2023), which however lack guidance and evaluation of their effects (Zhao et al., 2023). Initial evidence suggests that explicit pursuit of RRI in research projects improves communication, inclusion, and reflection, especially when time and space are provided (Taylor et al., 2023), while substantive take-up in project work appears challenging (Zhao et al., 2023). The perspectives of project stakeholders on RRI are likely to be diverse and can trigger creativity, whereas ambiguity can lead to inaction (Prutzer et al., 2023). The implementation of RRI in projects thus requires flexibility and continuous reflection from researchers (Forsberg and Thorstensen, 2018), who might still not see RRI as "good science" (Hove and Wickson, 2017). Disciplinary tensions can imply that RRI activities will be parallel and even in conflict with the actual research focus of a project because of institutional logics (Forsberg et al., 2021). Project management should therefore carefully ensure that the RRI dimensions of anticipation, engagement, reflection, and action are integrated flexibly in research practice to facilitate experimentation and learning (Ulnicane et al., 2023). The capabilities of project stakeholders to pursue RRI can benefit from such learning, which can be enhanced with formal and informal training (Ogoh et al., 2023). However, exactly how research projects could be set up to facilitate RRI remains unclear.

The SA of research and innovation projects is challenging at earlier research and innovation stages, during which such assessments are actually of particular value, because projects can still be redesigned or stopped to deliver more desirable and sustainable outcomes (Saille, 2015; Thorstensen and Forsberg, 2016; Matthews et al., 2019). Especially in the UK, sustainability is now part of reflections on implementing RRI in research practice (Pansera et al., 2020). Thus far, studies that integrate the concept of responsible research and innovation and the concept of SA are rare and remain vague about the research methods that are applicable to support the development of technologies fostering sustainable development in research and innovation projects (Matthews et al., 2019). Specific methods of SA, such as LCA, are occasionally mentioned in the context of RRI and trialled for early-stage technology (Owen and Goldberg, 2010; Bergerson et al., 2020; Bisinella et al., 2021; Parolin et al., 2024). Recently, provisional designs for assessments have been proposed for manufacturing, where gaps in SA remain (Parolin et al., 2024). However, if research and innovation policies aim to address the grand sustainability challenges, they need to align with approaches that support RRI at the level of projects and respond to the SA of research and innovation.

To address this gap, this paper develops a conceptual approach for use in research projects that aim to develop technology. The conceptual approach integrates methods required for RRI implementation—mainly participatory methods—with SA methods, including life cycle analysis, along typical phases of a project cycle. The applicability of the conceptual approach across a full research project cycle is illustrated with a case study of innovation in agricultural photovoltaics (agri-PV). Our concept combines overarching research policy goals with research project management and thus addresses the gap in how research methods that support RRI and SA can be applied in real research projects. We show that both RRI and SA are necessary to enable sustainable technology development.

This research makes several contributions. First, building on RRI, the conceptual approach developed shows how a research and development project should be set up to facilitate the achievement of socially desirable and sustainable outcomes. We demonstrate how the four RRI keys (anticipation, reflexivity, inclusion, and responsiveness) can be implemented throughout a typical research project cycle, from the initiation of the project to its completion. Second, we show at what steps the SA requires input from project stakeholders to facilitate the development of a socially, economically, and environmentally sustainable technology. This input triggers the reflexivity and responsiveness keys of RRI, which can imply reiteration of SA steps or even early termination of a project. Third, we show which approaches and methods of RRI and SA are applicable in each phase of the project cycle. Our conceptual approach describes the phases of a project in which both RRI and SA are embedded, and individual methods are linked to support both SA and RRI. Fourth, a case study on agri-PV illustrates how our conceptual integration of RRI and SA can be used in practice to develop and implement projects that engage the various directly and indirectly affected stakeholders to support sustainable and responsible technology development. The case study exemplifies a novel technology with sustainability and social properties not yet established, such as net energy production per area, pollution, and employment and landscape impacts, despite being an already tangible innovation applied in a few smaller pilots in practice.

This paper proceeds as follows. In the next section, we provide a conceptual and methodological background to the integration of RRI and SA at the level of research projects. Section 3 presents the resulting framework in detail. In Section 4, we apply the framework in a case study of agricultural photovoltaics to illustrate its use. In Section 5, we evaluate the applicability of the framework and discuss issues of implementation, consistency, and accountability. Finally, we conclude with the implications of the developed approach for research management and policy.

2. Conceptual and methodological background

The implementation of RRI and SA at the level of research projects requires operational concepts of RRI and SA that can be applied with the help of specific methods usable in the management of research projects. In this section, we first explicate RRI and the possibilities of operationalising it for research projects that follow a classic project cycle. Next, we specify how SA can be used in research projects to complement and implement RRI. The approaches and concepts of RRI and SA laid out in this section then form part of the integrative framework developed in Section 3.

A stylised concept of a research and development project life cycle forms the backbone of our approach. We used a simplified but comprehensive version with consecutive phases of initialisation, planning, design, implementation, and project closing that reflects the conceptualisation used for development-oriented research project management. These phases can overlap in research practice, and actual procedures could be more disorderly, for example, involving more iterations and various interventions going beyond project boundaries, comparable to a projectification at the front stage of presenting research to its stakeholders that differs from what the researchers actually do (e.g. Pal, 1998; Alexander et al., 2019; Fowler et al., 2015). Nevertheless, during initialisation, the idea and purpose of the project are established, including the actors involved, the scope of the project and possible funding. In the planning phase, the tasks, teams, timelines, and resources needed to fulfil the purpose of the project are determined. In the design phase, the contents and approaches of a project and its subprojects are specified in sufficient detail for implementation. During implementation, the planned research and development activities are carried out, such as conducting trials and experiments, data generation and analysis, or modelling. Monitoring and controlling is considered part of this phase, because it is closely linked to implementation and varies, depending on research and development situations, although from the perspective of the project manager, it might be an additional phase. Finally, in the project closing phase, the final results or products are established, interpreted, and possibly evaluated, which can include the identification of further research and development needs to be pursued in follow-up projects. The stylised representation illustrates a generic approach that can be adapted to more detailed project cycles and variations in research practices and specific projects. By integrating RRI and SA through practically applicable methods along the stylised project phases, we show how to contextualise a project and involve different stakeholders, as demanded elsewhere (Hart et al., 2005; Waters-Bayer et al., 2015; Biggs and Smith, 2003; Kristjanson et al., 2009).

2.1. Background on responsible research and innovation

RRI emerged from long-standing interests in integrating social and ethical considerations into research and from questions on how to deal with socially controversial research, particularly on nanomaterials (Owen et al., 2021b; Shelley-Egan et al., 2018). Its purpose is to direct research and innovation in response to social desirability through the inclusion of stakeholders and the wider public. At the beginning of its conceptual development in Europe around 2010, RRI has been aimed at the integration of science and its stakeholders and citizens to facilitate social acceptance of innovations, strengthen trust in science and legitimate European democratic institutions (Liu et al., 2022). Various crises in the food system, including bovine spongiform encephalopathy (BSE), foot and mouth disease, and dioxins in poultry, drove this reorientation of research governance (Owen et al., 2021b). However, it has become clear that RRI also needs to accommodate the grand challenges of European society, such as sustainable development, climate change, food security, and ageing societies (Owen et al., 2021b; Voegtlin et al., 2022; Rene von Schomberg, 2013). Since 2014, the European Commission has integrated RRI systematically in its research and innovation programmes, and RRI became a cross-cutting concept in Horizon 2020, although not with the aim of supporting ambitious changes (Saille, 2015). Tools and methods were developed to operationalise RRI for initial application in various fields, including climate engineering and precision medicine (Liu et al., 2022). Today, RRI has found its way into a wide range of different fields, such as smart farming, nanotechnology, synthetic biology, and gene editing, where RRI practitioners and researchers make use of a wider range of participatory and social research methods (Liu et al., 2022; Klerkx and Rose, 2020; Kokotovich et al., 2021; Pansera et al., 2020). However, besides first attempts to implement the RRI concept into practice (e.g. Fraaije and Flipse, 2020; Matthews et al., 2019; Espig et al., 2022; Forsberg and Thorstensen, 2018; Forsberg et al., 2021; Saille et al., 2022; Ulnicane et al., 2023; Zhao et al., 2023; Taylor et al., 2023), guidance on how to set up and execute research projects to achieve RRI remains lacking (Liu et al., 2022).

To make RRI applicable in the management of research projects, it needs to be broken down into meaningful and operational concepts that can be linked to project management methods. Stilgoe et al. (2013) proposed four dimensions, referred to as ARIR keys, to facilitate the application of RRI: anticipation, reflexivity, inclusion, and responsiveness. Anticipation captures futures of relevance to a particular research or innovation initiative by asking "what if ….?" questions, taking into account what is known, likely, possible, and plausible, including the contingencies (see also Nordmann, 2014). Reflexivity is a professional self-critique at the personal level to question one's own activities and assumptions and a reflection of commitments at the institutional level, considering that framings of issues are not universal and knowledge is limited. Inclusion entails the participation of stakeholders and members of the wider public in steering (governance) and evaluating research and innovation. Responsiveness implies the ability of research and innovation to change shape and direction in reaction to new knowledge, perspectives, and norms that emerge from anticipation, reflexivity, and inclusion activities. It is enhanced when the actors share clear commitments and have mutual obligations in a "co-responsible" implementation of RRI (Nordmann, 2019).

There are many methods for implementing ARIR keys, including those for "opening up" or "closing down" deliberations about research and technology development (Stirling, 2008). Whereas opening-up methods enable a consideration of the diversity of perspectives, needs, and experiences of stakeholders, closing-down methods ensure that decisions are made and respective actions are taken on how to progress with a research and technology development project. However, apart from more general deliberation about social desirability and sustainability, the anticipated sustainability impacts of a novel technology need to be assessed with additional approaches to inform the deliberations and decision-making of RRI.

2.2. Background sustainability assessment

SA encompasses the evaluation of the environmental, social, and economic impacts of a product or technology. Life cycle assessment (LCA) is a standardised assessment method that follows the norms of the International Organization for Standardization (ISO 14040, 14044). LCA is popular because it enables a comprehensive evaluation of the environmental sustainability of products or technologies over their entire life cycle that avoids any burden shifting across life cycle stages or environmental impacts. Methods such as social LCA (UNEP, 2020), life cycle costing (LCC) (Swarr et al., 2011), and techno-economic assessment (TEA) (Mahmud et al., 2021) are available to comprehensively evaluate social and economic sustainability, but they are less mature than environmental LCA (Valdivia et al., 2021). The ORIENTING Project (ORIENTING Project, 2022) recently identified additional methods such as material flow accounting, The Handbook for Product Social Impact Assessment (Goedkoop et al., 2020) or the life cycle working environment as alternatives for the economic and social assessment of products or technologies (Ko et al., 2018). Beyond methods for evaluating each sustainability dimension, SA also requires a common framework to ensure the comparability of the results obtained across sustainability dimensions. Such a framework is the life cycle sustainability assessment (LCSA), defined as a "transdisciplinary integration framework of models rather than a model in itself" (Guinée et al., 2011, 90). The UNEP/SETAC initiative defines LCSA more specifically as a combination of LCA, social LCA, and LCC (Valdivia et al., 2021).

Although different approaches are available for LCSA, its application generally proceeds in the four LCA steps: (1) goal and scope definition, (2) inventory, (3) impact assessment, and (4) interpretation. During the goal and scope definition, the aim and frame of the SA are set, and methodological decisions are made, such as the data sources or the methods to be used to evaluate the impacts. The inventory analysis gathers the data for the impact assessments, which are then used in the third SA step (the impact assessment) to evaluate the sustainability outcomes. The interpretation step combines the sustainability impacts and draws conclusions on the sustainability of the evaluated object.

Only a few LCSA studies relate to the agricultural sector, of which a review by Visentin et al. (2020) identified six studies, none of which evaluated technologies.[1] According to the review, the recurring challenges are (1) the interpretation of the outcomes and (2) the resource intensity of conducting an LCSA. Thonemann et al. (2020) found similar challenges for environmental SA for novel technologies, with additional challenges related to the uncertainty of the information gathered, the quality and availability of the data necessary for SA, and the comparability of SA of mature and novel technologies. The involvement of diverse stakeholders can help address these challenges, whereas tiered assessments that have increasing complexity levels can resolve the challenges of assessment resources (Neugebauer et al., 2015). Although the pursuit of both RRI and SA requires respective resources, synergies should arise when integrating RRI and SA because tasks and at least some data collected in each phase of the project can be shared by RRI and SA activities. Moreover, stakeholder involvement—and, thus, a good understanding of what potential impacts to consider and how to evaluate them and act upon them—can improve the outcomes of SA. LCSA outcomes can only contribute to shaping a more sustainable agricultural sector if they are reflected upon, fed back to the actors of the evaluated systems, and ultimately inform their actions. Strong stakeholder involvement in the SA steps and effective embedding of SA into a project's life cycle, as proposed in the framework presented in the next section, are essential.

3. The framework

We developed the framework as part of our involvement in an interdisciplinary research project that aims at guiding the assessment of potential sustainability outcomes of agricultural research and development projects, before the findings and technologies are seen ready to enter farming practice. The first task of the project was to develop a framework to guide such assessment in subsequent sub-projects, with a focus on the development of a range of technologies and involving researchers with diverse backgrounds. As the framework should be understood and applicable by all members of the sub-projects, we engaged them in several workshops to discuss early versions of the framework as well as potential cases for trialling it. The project members anticipated data limitations for assessments and shared uncertain social concerns and the views of stakeholders because of the novelty of the technologies. Furthermore, the SA of the technologies should both inform the technology development in the sub-projects and further research and development, as aimed for in prospective LCA. Thus, during our development of the framework to navigate such situations, RRI emerged as a key concept that needed to be integrated with prospective SA at the level of research projects and linked to specific methods to implement both RRI and SA.

We did not use a specific case to develop or pilot the integration of RRI and SA. The discussions among project members helped to sharpen the concepts of the framework and refine its inner workings, for example, through more appropriate placement of the LCA steps along project phases. Moreover, the project members found the need to identify methods that facilitate RRI and that could be appropriately fitted into SA for the consistent application of both concepts. This paper presents the refined integration of RRI and SA at the level of research projects. We arranged the integration around a stylised project cycle towards the end of the joint deliberations to reflect the current projectification of research (e.g. Felt, 2022; Torka, 2018; Ylijoki, 2016), which is typically governed within resource- and time-limited boundaries and consists of a sequence of activities that can leverage the elements of RRI and SA. Thus, the elements of RRI and SA are subordinated to the project cycle, as they should guide the governance of research. The stylised project cycle anchors them only in its own logic. We call the developed concept the RRI-SA framework.

RRI is a concept with normative directions, whereas SA delivers outcomes that help address the normative directions of RRI. Thus, we needed to specify the relationships between RRI and SA. Here, the introduction of the ARIR keys proved helpful in making RRI more tangible to the project members and enhancing the perceived role of SA, because the keys specify essential activities in the pursuit of RRI. The ARIR keys of RRI imply requirements for SA, such as including stakeholders. They also imply the roles of SA in supporting RRI, such as triggering reflexivity. Moreover, there is the grand social challenge that needs to be considered in RRI of devising research that facilitates sustainability. Besides the conceptual integration of RRI with SA, we needed to identify methods that facilitate RRI and appropriately fit SA. Such methods within SA should support RRI, while methods in RRI should bridge to SA. In this section, we begin by describing our conceptual approach, which integrates RRI and SA at the level of research and development projects. We then sketch out how the conceptual approach can be implemented with a range of methods that are available to respectively support RRI and SA. The concept developed in this section shows how the different steps, approaches, and methods of RRI and SA are aligned in a research and development project to support the development of sustainable and socially acceptable technology.

3.1. Conceptual integration of RRI and SA

The conceptual approach, which integrates RRI and SA, focuses on the engagement of stakeholders over an entire research and innovation project in which RRI should be achieved. Links between SA and RRI can be established for different research and development projects, for instance, when developing products (e.g. plant-based meat), systems (e.g. agricultural production systems following agroecological principles), or technologies (e.g. agri-PV). RRI mainly attends to project procedures, whereas SA is mainly used for punctual evaluations of the sustainability of a product, system, or technology, such as evaluating the sustainability of a lab-scale photobioreactor prior to scaling it up. Our focus is on a technology that is being developed. SA follows specific steps and RRI corresponding keys. The points of applying these steps and the methods to support specific RRI keys can be located in the management cycle of a

[1] No study evaluated technologies. Instead these studies cover production of soybeans (Zortea et al., 2018), cultivation of olives (Luca et al., 2018), dairy production (Chen and Holden, 2018), production of animal proteins (Scherer et al., 2018), use of soil and forests in mangrove management (Moriizumi et al., 2010), and alternatives in forest management (Pizzirani et al., 2018).

research project. However, SA is procedural, consisting of several steps that build on one another and require data on the technology developed and its anticipated application context. In the first phases of a research project cycle, such data are likely to be insufficient, but a prospective LCA can generate preliminary SA findings during a research project to inform the RRI keys of anticipation and reflexivity, leading to respective adjustments in the research project and the technology developed before project closure. As more data become available in later phases, the SA can provide more input to the anticipation key, but the reflexivity and responsiveness keys become more relevant. Thus, the anticipations of the SA should inform the reflexivity and responsiveness keys towards the end of the project cycle and follow-up projects.

In the first two to three phases of a research project (initialisation to design), methods that open up deliberations dominate, given the need to explore the technology to be developed and its context (Pärli et al., 2024). In the last two phases of a project (implementation to project closing), closing-down methods dominate because evaluations are finalised and decisions are made on technological design and governance (Stirling, 2008). It is important to explicitly name and plan these phases, since opening up a project in a closing phase can question the work done up to that point. However, sufficient time should be planned for phases of projects in which deliberations have to be opened up, since the social desirability and sustainability of the developed technology depend on whether the expertise, needs, and concerns of the affected stakeholders are considered. Fig. 1 describes the links between the research project cycle, SA, and RRI methods and keys.

Phase 1: In the initialisation, framing, and understanding phase of a research project, the project should support RRI through the inclusion key—that is, the involvement of stakeholders and the wider public in framing the project and creating a shared understanding of its scope, content, and purpose (see Table 1 for a brief summary of the content of the five phases). The anticipation key is important, as in this phase, stakeholders and project members must anticipate plausible features of the technology to be developed in the project and its impacts and application contexts. This enables project managers to set up a research project and an SA that are responsive to these features and the respective concerns of stakeholders, which should be reflected in the goal and scope of the SA. It implies that research project managers must anticipate stakeholders who should be involved in the project. Project management and researchers, as well as the involved stakeholders, can engage in mutual reflexivity during anticipation activities, but both the reflexivity and responsiveness keys will have a greater bearing on project management in later phases when the project and the SA are implemented in detail.

The SA does not start directly with the initialisation phase of the project. However, the outcomes of the first project phase should directly feed into the goal and scope definition of the SA in Phase 2 of the project. Deliberations in this first phase should include all teams involved in the project, including SA experts. This fosters a shared understanding of a project's aims and scope among the project team. As part of the deliberations, SA experts can inform the management of the project and the development of the technology from the start. Methods that open up deliberations to identify, inform, and involve stakeholders should also increase awareness of SA and its potential usefulness early on.

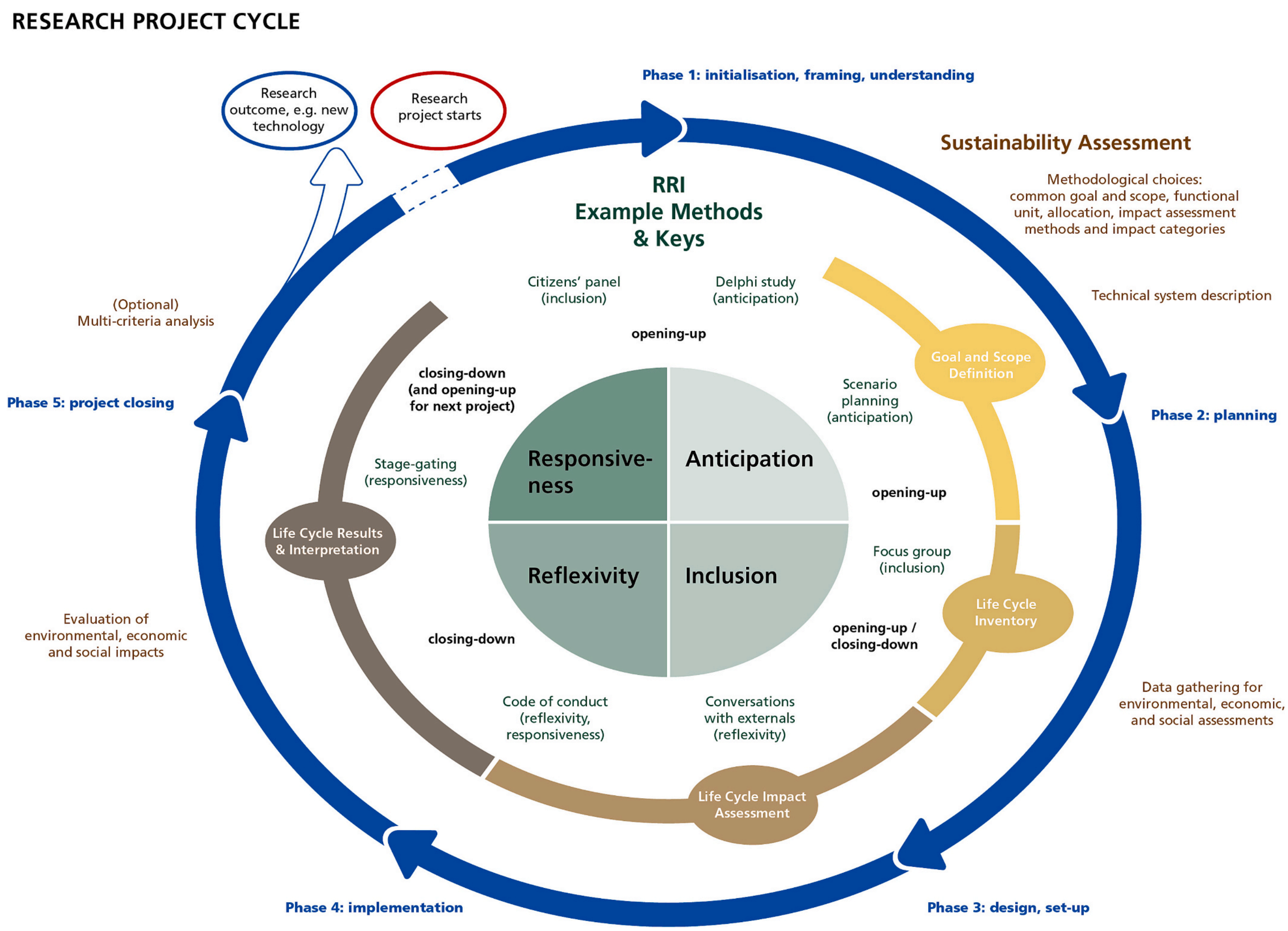

Fig. 1. Complementarities between the research project cycle, the four life cycle sustainability assessment steps, and the responsible research and innovation (RRI) keys.

Table 1
Key RRI and SA activities of the five phases of the research project cycle.

Project phase	Key activities of phase	Selected references[a]
1: Initialisation, framing, and understanding	Involve stakeholders and wider public in framing the project and creating shared understanding of its scope, content and purpose.	Concepts: Grin (2000); Nordmann (2014)
	Anticipate plausible features of the technology and of its impacts and application contexts.	Methods: Selin (2011); Miller and Bennett (2008); Hamilton et al. (2019)
2: Planning	Specify the goal and scope of the research and development project and of the sustainability assessment.	Concepts: Schomberg (2014); Fleming et al. (2021); Matthews et al. (2019)
	Specify system boundaries and plausible scenarios of the technology. Identify social desirability and sustainability issues of concern, including indicators and data needs. Facilitate project ownership among stakeholders.	Methods: Brier et al. (2020); Schomberg (2013); Urias et al. (2020)
3: Design and setup	Reflexively set up the research and development activities based on previous anticipations and participatory decisions. Conduct a preliminary sustainability assessment. Accommodate space for technological design options.	Concepts: Guston and Sarewitz (2002); Simon (2017) Methods: Wickson and Forsberg (2015); Coleman et al. (2016); Sanders and Stappers (2008)
4: Implementation	Conduct the research and development of the technology.	Concepts: Fisher et al. (2006); Wittrock et al. (2021)
	Reflect on emerging issues and the preliminary sustainability assessment. Perform the full sustainability assessment.	Methods: Asveld et al. (2015); Berne (2005); Beaudoin et al. (2022)
5: Closing	Respond to key insights of reflexivity, social desirability and sustainability assessment. Evaluate project outcomes.	Concepts: Jenkins et al. (2020); Fraaije and Flipse (2020); Macnaghten and Owen (2011)
	Draw up guidance for the further development and governance of the technology.	Methods: Chilvers and Kearnes (2020); Stitzlein et al. (2020)

[a] Stilgoe et al. (2013) is a generally useful source across all phases, and Chilvers (2010) provides material on methods for most phases. The work cited on methods often also covers concepts.

Phase 2: In the planning phase, the goal and scope of the research project and the SA are defined in greater detail. The inclusion key is still important, as there is a need to support participation and ownership among stakeholders. However, the inclusion key of RRI can be of lesser importance if the project consistently and transparently captures public and stakeholder concerns and desires established in the first phase. The anticipation key remains important, even though the focus in this second phase is on implementing the findings of anticipation from the first phase of the project. Project planning that is responsive to anticipation activities should be more detailed. Thus, more detailed anticipation may be required to reflect planning demands, and there should be more reflexivity on the part of the project team and stakeholders as compared to the first phase.

The goal and scope of the SA are defined in this phase to make them technology-specific and to describe the technology to be analysed, its function and, in lesser detail, the reference technology (the technology supposed to be replaced). The system boundaries are set following the findings derived from the inclusion and anticipation activities of the project's first phase. They define the system to be quantitatively analysed during the SA in terms of time horizons, geography, and stages and processes over the life cycle of a technology. Scenarios of the technology's development have to be specified, based on anticipations of plausible evolutions of the technology, such a scale, locations, uses, impacts, and governance of future applications. Further, the chosen SA methods should correspond with the anticipated sustainability issues of a technology and matching indicators. Methods that open up anticipation in RRI provide valuable input into specifying plausible scenarios of the technology's development (Stirling, 2008). Methods for supporting anticipation and inclusion also help discern the sustainability issues relevant to the stakeholders involved. Fitting indicators, data needs, and potential data sources for the SA should be identified towards the end of the goal and scope definition step of the SA, possibly with some stakeholder involvement. Once the goal and scope are defined, the inventory step can be initiated. Accessing the identified data sources, involving stakeholders in accessing data, and defining the questions to be asked to gather data are part of this step.

Phase 3: The design and setup phase draws on anticipations of the preceding phases. The reflexivity key is of great importance, as project managers and researchers should accommodate the anticipations in project design and setup to support the responsiveness key of RRI. Similarly, the SA should respond to anticipations and thus involves reflexivity. The inclusion key can be of lesser importance here but is implied when stakeholders and the wider public play roles in the research (e.g. in living labs or surveys), for which terms are established in this project phase. Rather than opening up deliberation, decisions in this phase close down previous deliberations (Stirling, 2008).

Based on the anticipations of the previous phase, the SA experts gather all necessary data for SA to complete the inventory analysis step. They initiate the impact assessment step and calculate preliminary SA results for the default setting and the anticipated scenarios of technology development. These outcomes can trigger reflexivity when they are inputs to RRI that are closing down deliberation to inform further decisions in project management and research. Adaptations to the inventory or even to the goal and scope are possible in the case of unexpected preliminary outcomes. Such reflexive adaptations can support the responsiveness key of RRI. This phase requires options for adapting the design of the technology based on SA outcomes. Hence, a preliminary sustainability impact assessment is useful as early as the third phase of the project cycle.

Phase 4: In the implementation phase, research and development activities are implemented and carried out in accordance with anticipations and the reflexive decisions made on them in the previous phases. Deliberations are closed down, and the responsiveness key dominates this project phase, because the research and development activities need to be responsive to the anticipatory and reflexive decisions made. However, as research and development proceeds and the SA yields results, unforeseen findings and issues may emerge that require researchers to be reflexive. If stakeholders are actively included in this phase, their reflexivity should also be triggered.

The third step of the SA is the actual impact assessment, which reaches into the implementation phase of the project's life cycle because adaptations are potentially necessary. Project members and stakeholders discuss the results of the SA in relation to the defined goal and scope in the results and interpretation steps of the SA. Methods that support reflexivity and responsiveness but close down deliberations are used to settle the sustainability issues to be further discussed. The need to consider RRI and SA outcomes in technology development implies that this phase should, in practice, be comparatively long to capture opportunities to trigger reflexivity and responsive technology development.

Phase 5: During the project closing phase, the responsiveness key is critical because project outcomes should be responsive to the anticipations and reflexive activities of the previous phases. This implies that project managers should transparently communicate project steps and outcomes, as well as RRI and SA procedures and outcomes, to all stakeholders and the wider public to support trust and accountability (Genus and Stirling, 2018). However, the inclusion and reflexivity keys are also important because all stakeholders and the wider public should understand the project outcomes, such as technologies developed and related research findings. This invites reflexivity among them and among the researchers as they engage in evaluating project outcomes. This phase is likely to entail informal anticipation among stakeholders and the wider public regarding the implications for applications and further technological development. Such anticipation can be formalised in this final project phase with appropriate methods, thereby informing future projects that aim to advance the research and development of the technology in focus. All project members and stakeholders should interpret the final results of the SA during the project's closing phase. Multi-criteria analysis can optionally be conducted with stakeholder input in line with responsiveness and reflexivity keys. Finally, project members can reflect on lessons learned from the application of the SA for future projects together with stakeholders.

Although the five project phases typically follow one another, they should also account for iterations and interactions between the RRI keys or the individual steps of the SA. Revisions of the goal and scope of the SA based on findings from the inventory are, for example, possible in the design or implementation phase. The approaches that close down deliberations in the last two phases of the project cycle can help ensure that the feedback loops inherent in the SA come to an end. The methods that support RRI and are applied in SA are described in the next sub-section.

3.2. Implementation of RRI and SA methods

For each ARIR key of RRI, different methods are available to directly and indirectly engage affected actors in a research project (see Fig. 2). Anticipation can, for example, be supported with a Delphi study, in which stakeholders anonymously explore different futures of research or innovation activities (e.g. Brady, 2015; Brier et al., 2020; Jiang et al., 2017; Rikkonen and Tapio, 2009). Scenario planning with workshops could convene stakeholders (e.g. Ehlers et al., 2022; Duckett et al., 2017; Ernst et al., 2018; Fleming et al., 2021; Oreszczyn and Carr, 2008). The reflexivity of researchers or innovation developers can be generally facilitated with a code of conduct or standards, against which actual aims and practices pursued in a research or innovation project are reflected, or through conversations with non-scientists or other scientists (e.g. Berne, 2005; Busch, 2011; Schomberg, 2013). Inclusion implies widening the participation to larger groups through, for example, citizens' panels, consensus conferences, or living labs (e.g. Beaudoin et al., 2022; Boogaard et al., 2008; Chilvers, 2010; Dell'Era and Landoni, 2014; Hörning, 1999). Responsiveness can be facilitated through stage gating, in which an evaluation is carried out at the end of each stage of the project and decisions on further progress are made. Other options include transparency mechanisms that support accountability or a moratorium if potential responses are highly contested among experts and in wider society (e.g. Blok et al., 2019; Cooper, 1990; Macnaghten, 2016; Macnaghten and Owen, 2011). A more comprehensive list of methods available per ARIR key can be found in the supplementary material.

Similar to RRI, particular methods can support certain steps of SA, as illustrated in Fig. 3. Many of these methods can benefit from the use of methods supporting RRI keys. Sustainability issues to be covered in the

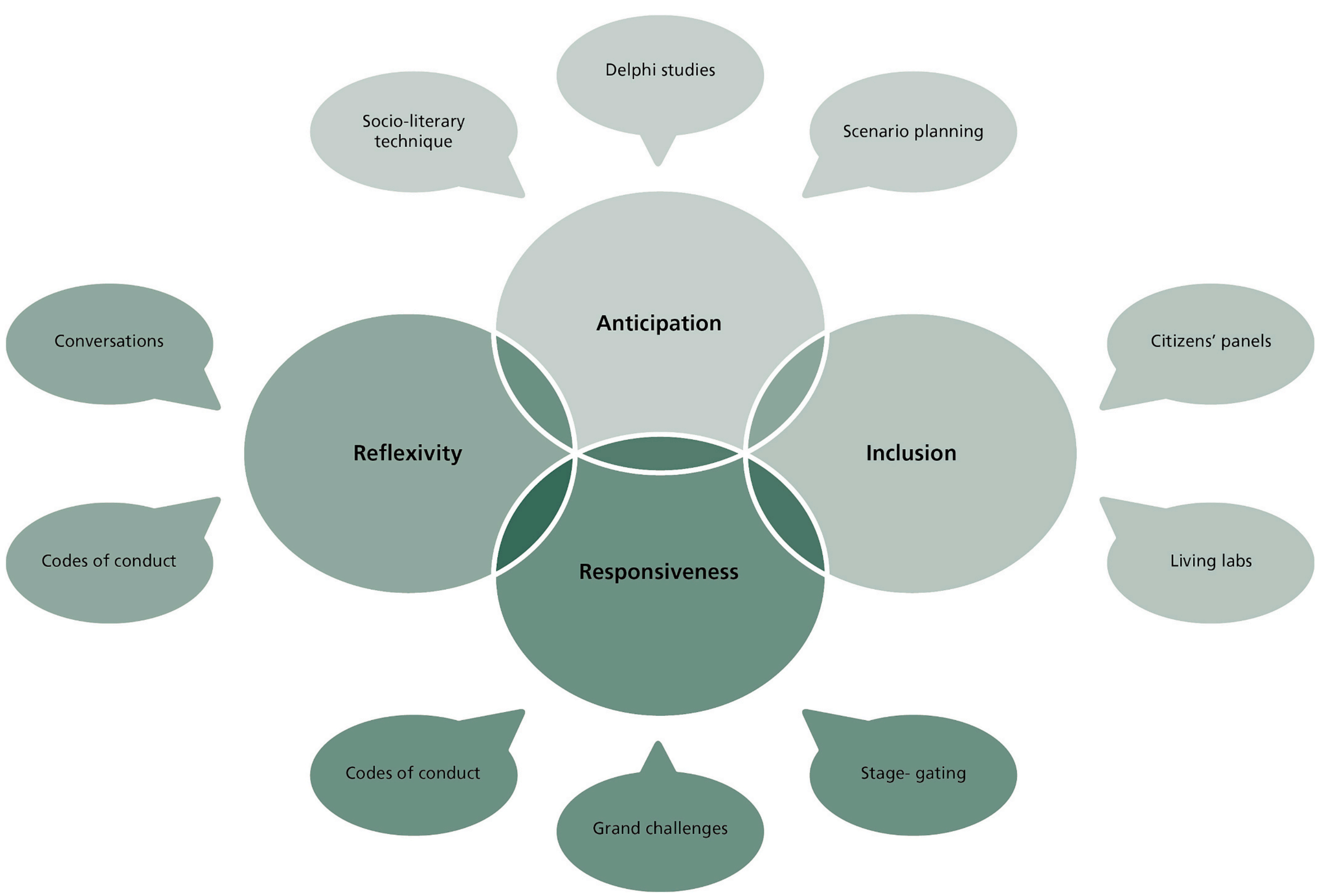

Fig. 2. Illustration of methods that can support specific ARIR keys (anticipation, responsiveness, inclusion, reflexivity) for responsible research and innovation (RRI).

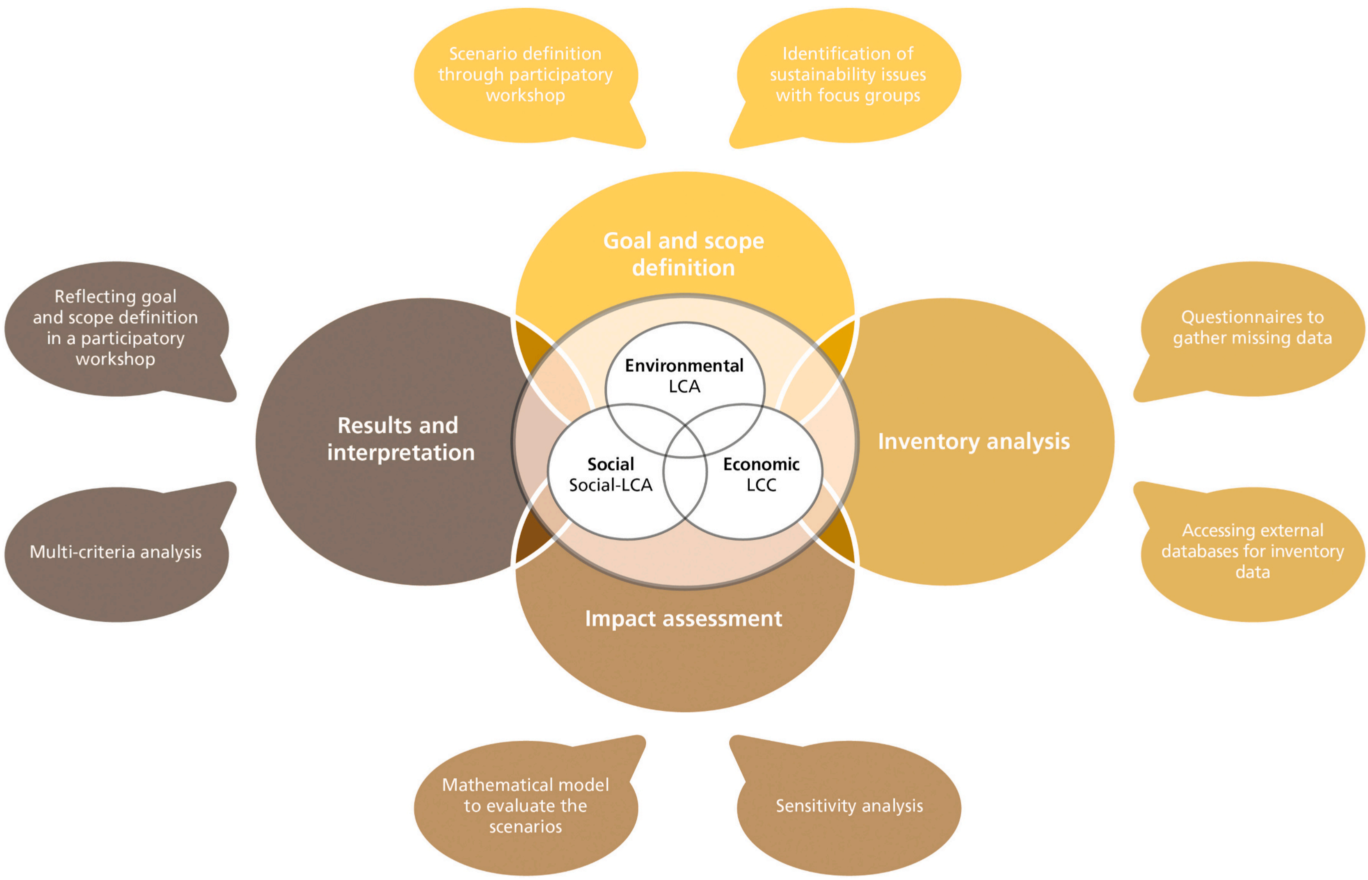

Fig. 3. Examples of methods and tasks per sustainability assessment stage. LCA: life cycle assessment, LCC: life cycle costing, social LCA: social life cycle assessment.

SA during the goal and scope definition can, for example, be identified in focus groups used to support the anticipation key of RRI.

The phase of the project and the information needed for the SA guide the selection of appropriate methods (see Table 1). To facilitate RRI and to fit in SA, methods within SA and methods that support RRI and bridge to SA are required. Moreover, consideration of all sustainability dimensions (environmental, social, and economic) is important. However, linking methods to individual dimensions is not necessarily straightforward, particularly when they are differentiated across the phases of research projects.

Ultimately, the purposes, features, and application contexts of methods to support RRI and SA in a specific research project need to be carefully considered, and the rationales of respective decisions as well as any application issues should be documented. This should not only help ensure transparency but also aid in achieving consistency of methods over the entire project in line with the chosen goals and scope.

4. Case study

In this section, we show how the RRI-SA framework developed in Section 3 could facilitate the responsible and sustainable development of agri-PV in Switzerland. This application is based on a single case study that is a sub-project of an ongoing interdisciplinary research and development project in which we are involved and were developing the RRI-SA framework. This pilot case study reveals how the combination of open design options, the uncertainty related to them, and the unknowns linked to the early-stage development status make agri-PV an ideal case for exploring our approach. Moreover, some project members with experience in agri-PV for soft berries contribute to the expectations of stakeholders. The single case study enables us to explore our framework in depth; however, the generalisation of our findings to other technologies and settings demands careful reflection and adaptation.

At our institute, we have developed a project to guide the responsible development of socially accepted and sustainable agri-PV with soft berries grown under shelter on which there is ongoing research. The project team is led by agronomists and social, natural, economic, and LCA analysts who conduct the research and assessments. The extended project team includes external expert advisors, such as foreign agri-PV researchers, and stakeholders, such as national photovoltaics and fruit growers' associations, who provide direction, advice, and input into the project. The project has started but is still in its early development stages. Although experts at our institute have experience with agri-PV on site, new commercial agri-PV installations in Switzerland are enrolled as pilots that provide data and serve as references.

4.1. The agri-PV research and development project

Agri-PV is a novel technology that combines agricultural production with electricity production from photovoltaic cells and has been gradually finding its way into practice, with a few pilot plants in Europe and some larger deployments in China and Japan (Weselek et al., 2019). Depending on the sites, the crops grown, and the specific technologies used, there are many types of agri-PV installations whose sustainability performance and social acceptance have yet to be systematically explored (Wagner et al., 2023; Cousse, 2021; Wolsink, 2012). Ongoing projects at our research institute examine the conditions for growing soft fruits with agri-PV. Besides optimising fruit production, there is the question of optimal technology for electricity production (Junedi et al., 2022; Hollingsworth et al., 2020). Furthermore, the social desirability and sustainability performance of agri-PV installations in general and of specific designs remain unclear, with the possibility of their site specificity in the Swiss context, for example, in terms of perceived landscape aesthetic impact (Kienast et al., 2017; Ioannidis and Koutsoyiannis, 2020). In our case study, the agri-PV installations consist of photovoltaic panels installed either on fields or as part of greenhouses to protect soft fruit crops from natural hazards, such as intense sunlight, heat, or heavy rainfall (Laub et al., 2021) and to produce electricity from renewable resources.

4.2. Application of the RRI-SA framework

We apply our RRI-SA framework, considering all five phases of the project cycle of the ongoing agri-PV sub-project as part of the larger project in which we developed the framework. The application in the agri-PV project illustrates the working principles of our framework. It also helps us plan the agri-PV project, whereas the project enables us to identify potential future requirements for the framework. The first phase has started. This is typical, as the initialisation of research projects can have diverse origins preceding the first conception of a project idea. However, the first phase is also about framing the research and establishing a shared understanding. This is where the concepts and methods of the RRI-SA framework begin to come into play, as we sketch out for each phase of the agri-PV project.

Phase 1: According to our RRI-SA framework, the inclusion and anticipation keys of RRI imply that the activities of the leading project team to support RRI and SA of agri-PV start with a desk-based stakeholder analysis to identify Swiss and key external stakeholders. The leading project team discusses the stakeholders of interest to be included, such as soft fruit producer organisations, planning authorities, and utilities, landscape, and renewable energy associations. Topical and disciplinary experts become part of the extended project team, either as researchers or as external advisors. They assist in choosing agri-PV projects operating at farms to be partners in the project, identifying initial data sources, and establishing first contacts with these partnering agri-PV projects to access data for the SA.

The project team reviews the scientific literature to compile the first sustainability impacts important in the context of agri-PV, such as embodied and produced energy, pollution during production of PV cells, economic costs and revenues, work requirements and conditions along the supply chain, and biodiversity and landscape effects. The team agrees that considerations of impacts should be left open until appropriate methods of closure are used in later project phases, and that subjective weighting of the various impacts by project members should be avoided. The findings from the literature review are used to inform a Delphi study that starts at the end of this project phase in which topical and country experts participate to identify and refine further anticipated impacts, and questions of social desirability and acceptance of agri-PV. Alternation between RRI and SA approaches and methods facilitates systematic and comprehensive collection of all data and information relevant to SA, indicator selection, and wide support and acceptance of subsequent analyses.

Phase 2: One part of this second phase is linked to the system boundary definition for the SA. The initial description of the technology of agri-PV by the project team covers all life cycle stages. This includes the production of the photovoltaic cells, electricity grid connection, construction of the greenhouse, operating the greenhouse and the PV plant, electricity production, and the replacement of equipment over the 20-year lifespan of the installation and the end of life of the greenhouse and PV plant. The inputs needed for greenhouse operations, such as water, fertilisers, and pesticides, are also considered. The choice of these system boundaries is in line with a recently published assessment of agri-PV (Ravilla et al., 2024). We use a focus group with academic and industry (agricultural and photovoltaics) experts to validate the description of the technology and to define the reference systems to which agri-PV for soft fruits in Switzerland should be compared. Options for reference systems are greenhouses, open field cropping, photovoltaics on open fields, or other forms of electricity production. These reference systems serve as benchmarks for evaluations because of their direct links to agri-PV.

Based on the Delphi study that starts in Phase 1 and continues in this phase, alternatives for possible scenarios for the considered technology are formulated in a participatory workshop with the same experts (see Ehlers et al., 2022). Important variables for such alternative scenarios are different technologies, different ways of using agri-PV to produce fruits, different sizes, locations, and diffusion of agri-PV in Switzerland, as these co-determine impacts are considered in the SA. Larger agri-PV installations imply higher yields and are thus likely to have fewer environmental impacts and economic costs per kg of produced fruit while potentially requiring more labour covered either through more employees or longer working hours. More specifically, a comparison of vertical bifacial and stilted agri-PV (Krexner et al., 2024) or mono-axial or bi-axial tracking PV systems (Ravilla et al., 2024) can help stakeholders choose PV systems based on sustainability aspects. The spacing of the PV panels and, in turn, the shading and irrigation needs of the underlying plants is another parameter that can be chosen to optimise environmental, social, and economic sustainability (Ravilla et al., 2024).

To evaluate the social, economic, and environmental sustainability of agri-PV in Switzerland, we use LCA, LCC, and social LCA based on methods and data identified through the literature reviews of the project team in Phase 1 of the project. We use two functional units to express the results: 1 kg of soft fruits and 1 kWh of electricity produced. This ensures better comparability with existing SA studies of reference systems and is in line with the opening-up strategy. However, it is still difficult to judge whether agriPV deployment will be driven mainly by electricity or food production. Experts involved in the Delphi study and focus group discussions inform and validate respective decisions, especially related to the choice of indicators for social LCA, for which participatory approaches have been proposed (Bouillass et al., 2021). We use the Swiss Agricultural Life Cycle Assessment impact assessment method and its 19 indicators to quantify the environmental impacts of agri-PV systems (Douziech et al., 2024). Our data sources for the inventory stage are the developers and operators of the agri-PV sites at the partnering farms. For missing data, we use generic LCA databases, including ecoinvent (ecoinvent, n.d.) and Agribalyse (AGRIBALYSE, 2023) where possible. The Delphi study includes iterations in Phase 2 that provide suggestions of anticipated sustainability impacts to consider in the SA and facilitate coverage of all relevant aspects.

Phase 3: Much of the work of the project team in this phase is dedicated to conducting the SA. It includes extensive data collection and the calculation of preliminary impact assessment results. The interdisciplinary project team develops questionnaires to gather the necessary data from the partnering agri-PV sites that are sent to their developers and operators. Among the required data are fruit yields, installed PV capacities and materials used, the working hours of the field workers, and the machines used on the field together with the hours operated. We use focus groups involving representatives of stakeholders who are concerned with the social dimension of agri-PV to refine the questionnaire for the social sustainability dimension, taking into account the findings of the Delphi study finalised in Phase 2. The questionnaire is used to survey the anticipations and concerns of a larger set of members of stakeholder groups and the public in Switzerland. This helps us define the social variables of the SA, generating necessary social data and insights into social desirability and acceptance of agri-PV.

Visits of the project team to the partnering agri-PV sites involve site-specific stakeholders and help validate the comprehension of the technological system, ascertain impact variables, and gather data only available from the agri-PV sites. Next to site-specific data, we use generic data from databases, published literature, or other projects to describe the reference technologies and to fill potential data gaps of the investigated system.

The preliminary results of the impact assessment trigger reflexivity and responsiveness, as they help the leading and extended project team reflect on the study and technology design choices of agri-PV plants and adapt scenarios or the chosen impact categories of the SA, if needed. In this phase, we present preliminary results and SA choices that aim to support the reflexivity key of RRI. The social survey that generates further anticipations through the unidirectional inclusion of a wider set of agri-PV stakeholder members and the public in Switzerland triggers further reflexivity.

Phase 4: The reflection that started at the end of Phase 3 with preliminary results of the SA and the social survey ends in Phase 4. Adaptations to the goal and scope of the SA are no longer foreseen. The project uses strategies of RRI that close down deliberations to make responsive decisions on how to finish the project and to draw conclusions on the sustainability of the evaluated technology in comparison to the reference scenario. We compare the different design alternatives in terms of their sustainability and social desirability. For example, Ravilla et al. (2024) identified a bi-axial tracking PV system as more cost-effective and having lower environmental impacts than a mono-axial tracking PV system, due to the lower number of PV systems to be installed and their limited shading impact. Krexner et al. (2024) also found vertical bifacial PV systems to be environmentally beneficial compared to stilted agri-PV.

In this phase, the project team, including the technology developers and agronomists of the project team, becomes reflexive and considers how to respond to the findings of the SA. Although some of the participatory approaches in Phase 2 contribute to a good understanding of the impact indicators used, it is important to repeat and complement these explanations in this phase. This helps ensure that the findings of the SA are well understood. In a workshop with key stakeholders, including further agri-PV technology developers, operators, regulators, and the project team, the implications of the findings are discussed in depth to explore technology design and governance options that support the responsiveness dimension of RRI. In light of Ravilla et al.'s (2024) findings, stakeholders could, for example, decide to install bi-axial tracking PV systems instead of planned mono-axial tracking PV systems. Possible alterations of technology design mean that Phase 4 must be long enough to accommodate the re-design of the technology. Project members and stakeholders may also decide to stop the pursuit of a certain technology because of insufficient social desirability and sustainability.

Phase 5: The interpretation step of the SA comes to an end in this final phase of the project. The SA is not simplified into a single overall impact score because the leading project team decided in Phase 1 to avoid subjective weighting of the various impacts team and that consideration of impacts should be left open. This reflects the aim of making trade-offs visible rather than resolving them to support the identification of options for improvement in every criterion that is seen as underperforming. There is no provision for adjusting the decisions made during the project or ignoring the findings of the participatory process with stakeholders at the end of the project. Instead, stakeholders discuss the technology in light of RRI and their interpretation of the results of the SA that are presented along multiple indicators capturing all dimensions of sustainability and the findings of the social survey to suggest responsible uses and governance of the technology and further development and assessment needs. This is done in two steps. Initially, the results are presented in a larger workshop with representatives of all stakeholders. Subsequently, a focus group consisting of the project team members and a sub-sample of the representatives formulates responsible uses and governance of agri-PV in Switzerland, as well as further development and assessment needs, based on the discussions in the larger workshop. These formulations are made accessible to all stakeholders and the public, along with the outcome reports and documentation of the project as the conclusion of the project approaches. Further research projects on agri-PV can then build on these insights and recommendations in the pursuit of continuous RRI.

5. Discussion

Our RRI-SA framework integrates RRI and SA by aligning the methodological steps of RRI and SA along a stylised research project cycle with the aim of lifting synergies of the approaches. The SA results are important in supporting the reflexivity key of RRI, for which suitable methods and approaches were limited and, with the exception of codes of conduct and conversations with externals (Stilgoe et al., 2013; Berne, 2005; Busch, 2011), impractical at the level of research projects. These synergistic effects of RRI and SA are only possible with the careful planning of projects. In our case, the agri-PV project was planned with the framework in mind, which might explain its general applicability. However, the applicability of our framework could prove more challenging and may require testing in research and development projects that are planned before attempting to implement the framework. Nevertheless, certain RRI and SA activities are applicable only in specific phases, while other activities are useful in a variety of phases.

To illustrate, SA benefits from anticipation at the outset of a project, while it can also inform anticipation, which in turn informs responsiveness, particularly at later stages, when assessments can be more thorough. In general, anticipation is more beneficial when the project is equipped to respond to it. Concurrently, reflexivity is essential for the responsive adaptation of technology development and of the SA. Failure to address all RRI keys at the earliest possible stages of a project may result in the ineffectiveness of RRI keys in subsequent phases. Therefore, it is essential to ensure that the specific RRI keys are not overlooked in any phase to identify opportunities to utilise them throughout the project cycle and the SA. This will facilitate the comprehensive implementation of RRI keys, particularly those related to reflexivity and responsiveness. It implies that research projects should not only have their possible outcomes in mind but also focus on the procedures, methods, and approaches with which the various project developments can be managed. Besides pooling resources, data gaps are more easily filled, given the advantage of combining RRI and SA techniques. This is not only particularly relevant for otherwise missing data for SA that are approximated based on findings from RRI methods but should also help save resources through sharing them among SA and RRI activities.

The aim of the case study was to illustrate a possible application of our framework and to identify issues that warrant attention. The single case study of agri-PV allowed us to explore the applications and related issues in detail, which would not have been possible with a much less advanced technology on which there is very little public discussion, stakeholder engagement, and limited LCA data. With a single case, we cannot claim completeness and full applicability of our framework across technologies, research projects, and their settings. However, we focus on aspects that appear to concern most research and development projects and point to possible needs for adaptation of the RRI-SA framework and ways to implement it for deviant technologies and project settings. The agri-PV case study shows that our RRI-SA framework is applicable throughout the research project cycle, from initialisation and planning to implementation and project closure. However, its contribution to the development of sustainable and socially desirable technologies depends on the resources and data available, the timing of RRI and SA activities in the project cycle, and the choice and application success of the methods used to implement them. For example, an RRI-informed SA of a less advanced lab-scale technology could be a prospective LCA that involves many expert-based assumptions and a very limited social LCA and economic assessment because of a lack of data (Douziech et al., in preparation). In such cases, the application of our framework could be led by fewer and less-informed experts. Such applications would be patchy, and insights generated from them would be more speculative, especially when involving less knowledgeable stakeholders. However, even in such circumstances, the application of our framework would be a first step towards facilitating RRI and the development of more sustainable technology, even when some adaptations and less effective implementation methods need to be used. This is mainly because we developed the RRI-SA framework for general applicability, and the methods to implement it consist of multiple options to make it flexible without losing its RRI and sustainability goals. Further applications of our framework and testing additional implementation methods and LCA datasets, complemented by open research data, should help refine its general elements and procedures and specify effective implementation methods. However, the research context needs to be facilitative, and researchers should be open or pushed towards this (Gold, 2021; Andreoli-Versbach and Mueller-Langer, 2014; Lacey et al., 2020).

Involving stakeholders, choosing the appropriate methods, and documenting decisions requires time and financial resources that are typically limited and should be included in the budget of a project. In addition to resource considerations, the selection and coordination of project stakeholders are critical for successfully applying our RRI-SA framework. Thorough stakeholder mapping during the first project phase (e.g. Leventon et al., 2016), detailed engagement plans and frequent information provision by combining approaches of the framework that are opening-up and closing-down deliberations are strategies for productive stakeholder involvement (Stirling, 2008). However, the inclusion of unusual stakeholders could also be valuable to avoid reification of established perspectives (Wicher and Frankus, 2023). It is important to explicitly acknowledge anticipation and, above all, show reflexivity throughout the project cycle to respond appropriately to stakeholders' concerns (Stilgoe et al., 2013). Potentially difficult to ensure is the continuous engagement of the stakeholders throughout the project (e.g. Neef, 2005). Feedback on our agri-PV case suggests that regular project meetings that set clear expectations and provide information from the project, even when they aim to close down deliberations, can help maintain their interest in the project. However, the project team needs to be open to all potential outcomes of the RRI-SA framework's application.

A key challenge is the timing of the SA, which is easily delayed in practice. The SA should start as early as possible, and the needed data should be available as early as possible in sufficient quantity and quality, covering all anticipated social and sustainability issues. This can often only be achieved towards the end of the project cycle when there is limited interest in reflexivity and scope to respond to the assessment. Preliminary assessments are an alternative to feed SA findings into the project, but they can be incomplete and lead to bias in the assessment, for example, when there is initially mainly photovoltaic cell manufacturing life-cycle inventory data available for an assessment of agri-PV that has many more facets. Similarly, the assessment of the economic viability of the technology depends on its impact on market prices, which are for example contingent on environmental and agronomic factors in the case of agri-PV. These uncertainties could be addressed to some extent with a techno-economic assessment that gradually becomes more refined as better data are generated over the course of a project or with follow-up projects (Buchner et al., 2018; Spek et al., 2020).

Although our framework provides general guidance and points of attention, it reflects a general lack of research on how to implement thorough techno-economic assessments in projects that meet RRI requirements. Our agri-PV case benefits from the coverage of pilot projects operating in practice, which are unlikely to be available for less advanced technologies on which, therefore, will be less data. Moreover, reference systems or technologies are important for the evaluation of technologies that were clearly specified in our case but may be more controversial in other cases (Tavella, 2016) and therefore need to be carefully handled in the application of our framework. Such issues can be mitigated with stakeholder and expert involvement to some extent, but the preliminary SA would still be less rigorous. The methods used to implement SA and RRI and their actual applications appear to be critical for the successful application of our RRI-SA framework. Our agri-PV case describes a set of methods. Others could be trialled for comparisons in the same case and in other technology cases and settings.

Applying the RRI-SA framework in research projects poses research practice to examine social desirability and sustainability at early stages of developing novel technology and responding appropriately with adjustments within individual projects. Although this helps to legitimise research and technology development, it can also mean that technological development will be drastically redirected or stopped if respective amendments of technology design turn out infeasible, based on the findings from stakeholder participation and SA. This option is often not in the interest of the technology developers but is required for projects focused on sustainability and social desirability. All of this implies that the researchers involved need to have or strategically acquire the skills and mindset to implement RRI and SA successfully in technology development projects (see Hove and Wickson, 2017; Ogoh et al., 2023).

Besides confrontation, the evidence on RRI and SA could be emphasised, and letting RRI and SA influence technology development projects, for example, in transdisciplinary project setups, could be considered a more subversive strategy (Herberg and Vilsmaier, 2020; Fitzgerald et al., 2014). However, as such, the RRI aspect does not specify what technology developers should exactly do to improve a technology, and an SA only examines the sustainability impacts of a technology, without specifying in detail how a technology should actually be changed to improve social desirability and sustainability. Thus, there is a need for explorations beyond our case of agri-PV on how to link the assessment and RRI outcomes to practically feasible technological options. In our case, we observed that reflexivity on the part of the technology developers is generally possible within our framework, but it could have little consequences for technological design and improvement within the cycle of a short project. This clearly hampers responsiveness within a project and implies that the conclusion of projects greatly emphasises developing responsive follow-up projects. A remaining concern is the use of the SA by some stakeholders to present novel technologies, such as placing agri-PV in a more favourable light (greenwashing) than it actually would have been as more evidence becomes available.

A final challenge is the fact that our RRI-SA framework originates from our engagement in research projects in Western Europe focused on technologies in the agri-food sector and may not sufficiently accommodate the specificities of other sectors and geographical settings. However, the RRI keys and proposed methods are generic. An extension to other types of projects and technologies should be feasible when the respective adaptations to fit their particularities are planned right from the start of applying the framework.

Transparency and access to data and information are needed both when running a project and after project completion. Transparency of the methods applied and research steps throughout the project is very important for accountability and for enabling open discussion of preliminary and final results within the project team and with stakeholders and the wider public (Genus and Stirling, 2018). Shared (online) platforms and the provision of information on, for example, questionnaires used in surveys, test setups or measurement results of, for example, fruit yields or working hours, facilitate internal traceability of outcomes. This implies a need for consistent recording of decisions in minutes, especially before closing down deliberations to make important decisions on the next steps (Stirling, 2008). After project closure, as much information as possible should be made publicly available so that those not involved in the project can learn and form an opinion on the sustainability of the technology of concern. This includes data, as data protection law allows, documentation of project steps, surveys carried out, their results, and data usage rights (Owen et al., 2021b; Lacey et al., 2020). Such information can, for example, allow for comparisons of sustainability assessments across projects (Sala et al., 2015). However, it is essential that public access to data and results is agreed upon with the technical partners involved at the beginning of the project.

A prerequisite for the broad implementation of the RRI-SA framework and guidance of project researchers is the consistency of funding instruments and research governance. A lean application of the RRI-SA framework in research would require limited specific expertise and skills that external collaborators or experts under contract could bring in. However, comprehensive SA and thorough facilitation of RRI are required. It requires substantial expertise and resources that should be planned and budgeted at the beginning of a project. Funding regimes may not always be fit for this purpose, which underlines the importance of promoting RRI at higher levels of research governance.

This discussion covered the mainly detailed implications that arose from the focus on research projects. Wider implications emerge from embedding projects that make combined use of RRI and SA in research organisations and higher-level research regimes. These concern a need to develop awareness, skills, and mindsets, besides structural changes that enable research practitioners and stakeholders to steer research and development projects towards the generation of sustainable and socially desired technology. Policy-level studies on research and innovation governance should now explore possible interactions with research practice on the ground. This will be especially important for technology that inflicts controversies that cannot be managed at the project level alone. Researchers and stakeholders of a novel technology could navigate RRI and SA beyond the boundaries of projects. In a research environment dominated by projectification, our framework could also help drive wider change in research governance supporting sustainability and RRI from within projects that may act like Trojan horses and might have emergent properties that challenge their environment (Barondeau and Hobbs, 2018; Pel, 2016).

6. Conclusion

This paper addresses the implementation of RRI and SA at the level of research projects, which is needed to make research and technology development practice responsible for the grand sustainability challenges of today. The developed framework integrates established RRI and SA concepts and methods consistently throughout a stylised cycle of research projects. Its applicability is illustrated in the case of agricultural photovoltaics. Benefits, challenges, and further implications of the RRI-SA framework are discussed to facilitate advancement of research on implementing RRI in research practice and SA of novel technology early on to responsively govern their development at the project level.

Our RRI-SA framework facilitates the implementation of RRI in research projects. This work complements earlier models for responsible research and innovation management, as it shows how RRI can be systematically and comprehensively translated from a higher-level concept into actual research practice. Within the framework, we develop a procedure for SA of research and development of novel technology at the project level that integrates RRI. This enables synergies between RRI and SA, both in the first steps of SA, when there are great unknowns and uncertainties surrounding novel technologies and research that require sound anticipation of developments and impacts for the SA, and in later steps, where SA can support the reflexivity key of RRI in much greater detail than previously suggested approaches.

The empirical case of agri-PV underlines that the use of the RRI-SA framework and the methods for implementing it in research projects will require financial and human resources that may often not be available. Research governance that aims for RRI not only in policy discourses but also in actual research practices and projects will need to make way for respective resources in policy and funding instruments that explicitly address the needs of individual research projects that aim at technology development. Supporting end-of-the-pipe science–society engagements, as they are now well established, will not be sufficient. Instead, public and private support for RRI and SA needs to either be built into technology development projects or be available as complementary funding or services.

Our study suggests that further research is needed on how best to organise and manage research projects to implement an integrated RRI and SA approach and to develop the needed skills, particularly when there are mainly engineers and natural scientists involved. In addition, research into how to embed the RRI-SA approach in research and funding organisations would be useful. As we developed the framework against the backdrop of agri-food technologies, there is a need for research on how to amend it for application in other sectors.

CRediT authorship contribution statement

Melf-Hinrich Ehlers: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Nadja El Benni:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Mélanie Douziech:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.respol.2024.105164.

Data availability

No data was used for the research described in the article.

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