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Paving the pathways towards sustainable future? A critical assessment of STI policy roadmaps as policy instruments for sustainability transitions

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ABSTRACT

Roadmaps and roadmapping techniques receive increasing attention in the Science, Technology and Innovation policy community, notably for the development of strategies and policies to address societal challenges and ambitious goals such as the SDGs. STI policy roadmaps are used to evoke future visions, align actor expectations and formulate, document, plan and implement public policies for long-term, ambitious sustainability goals. As a sophisticated strategic planning process, roadmapping seems appropriate for policy support aiming to foster sustainability transitions. Nevertheless, there is little research on the role and limitations of roadmaps as a policy instrument to support innovation for sustainability transitions. This paper critically assesses selected national and international policy and sectoral roadmaps that focus on technology areas and societal challenges relevant to sustainability and energy transitions. The assessment of the objectives, design features and embeddedness of roadmaps in policy processes shows that current policy roadmaps have several shortfalls. The paper outlines knowledge gaps and research priorities to understand how such limitations might be overcome and draws tentative lessons for future applications of roadmaps as policy instruments for sustainability transitions.

1. Introduction

Technology roadmaps are a prominent foresight and strategic planning technique used in technology management. A rich body of literature exists on technology roadmaps and other foresight techniques, and their applications (Fahey & Randall, 1998; McDowall & Eames, 2006; Phaal et al., 2004; Phaal & Muller, 2009). Notable roadmap applications include business planning, large-scale transition management (McDowall, 2012), the implementation of the 2030 Agenda and Sustainable Development Goals (SDGs) (UN, 2018), and other areas, such as policy making (Ahlqvist et al., 2012; Carayannis et al., 2016; Meissner et al., 2016; Miedzinski, 2015; Miedzinski et al., 2019).

At the interface of innovation policy and sustainability transitions, there is an ongoing academic and policy debate on the role of innovation policy to address societal challenges and foster transformational change towards sustainable economy and society (Diercks

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et al., 2019; Mazzucato, 2018; Schot & Steinmueller, 2018; Kuhlmann and Rip, 2018; Weber & Rohracher, 2012). The overarching rationale and objectives of innovation policy shift slowly towards addressing societal challenges and sustainability transitions to address long-term ambitious sustainability goals such as the SDGs (see e.g. UNCTAD, 2019; UN IATT and EC, 2021). There is a growing awareness among policy makers, notably in the EU, that innovation policies of conventional scope and forms are insufficient to address societal challenges; new transformative and mission-oriented approaches are necessary to tackle contemporary societal and environmental challenges, such as climate crisis, energy system transition or pandemics (e.g. Larrue, 2021).

New generations of challenge-oriented innovation policies must be designed to embrace the multi actor, multi-dimensional, coevolutionary nature of sustainability transitions (Geels et al., 2016, 2017; Geels & Schot, 2007; Köhler et al., 2018; Papachristos et al., 2013). They are inherently long term, open-ended and iterative processes that alternate between stability and change. Their complexity and uncertainty require reflexive policies and governance (Smith et al., 2010; Voss et al., 2006; Weber & Rohracher, 2012). As many choices and decisions about sustainability transition include a normative component, policies must anticipate and manage actor disagreement and value contestation about the direction of change and transition pathways, (Smith et al., 2005; Stirling, 2014).

Challenge-led innovation policies require new instruments and tools to enhance the design and implementation of policy. This paper discusses the role of roadmaps as strategic policy tools for Science, Technology and Innovation (STI) that bridge the design, implementation and evaluation of public policies. As a sophisticated, participatory, strategic planning instrument, roadmaps have the potential to become systemic policy instruments (Ahlqvist et al., 2012). Roadmaps can support challenge-led innovation policies to address SDGs or other goals of sustainability transitions. However, roadmap design and implementation should acknowledge and embrace the complexity, potential pathways, and uncertainty of transitions and cater for the diverse interests, long term visions and capacities of actors.

Despite the interest in roadmap application to policy processes, there is little research, especially on roadmap application to tackle societal challenges and foster sustainability transitions and SDGs. In light of the resurgent interest in STI roadmaps among policy audiences, it is necessary to analyse the role and limitations of roadmaps as policy instruments, and reflect on how they could be adapted and applied as strategic frameworks to promote transformative change and transitions to sustainability.

This paper evaluates critically 20 national and international roadmaps that address innovation areas and challenges relevant for sustainability transitions. The paper shows that STI policy roadmaps are used in diverse ways and have the potential to become a versatile systemic policy instrument to strengthen the directionality and temporal coherence of policy mixes. Roadmap development is done in several ways. Not all of them are useful, and some embody rather narrow views of the future that fail to represent the diverse perspectives, interests and the scale of systemic uncertainties involved in sustainability transitions. While evidence supports the utility of roadmaps across a number of governance processes, and the overlap with transition process characteristics may be an appealing prospect (Köhler et al., 2018), our assessment suggests that current roadmaps fall short in a number of ways.

The remainder of the paper is structured as follows. In Section 2, we introduce the theoretical and conceptual framework of the paper with areas and questions that guide the analysis. In Section 3, we analyse and synthesise the results of the assessment and summarize them in tables and taxonomies. In Section 4, we discuss critically policy roadmaps in the context of sustainability transitions. In Section 5, we conclude with a final reflection on the use of STI roadmaps as governance and policy instrument to stimulate transitions.

2. Research design

2.1. Roadmapping as a strategic planning and management tool

Roadmaps as a planning tool originate in innovation and technology management research, but they are also used in foresight and prospective studies (Saritas & Aylen, 2010). Roadmapping is defined as: 'a powerful technique for supporting technology management and planning, especially for exploring and communicating the dynamic linkages between technological resources, organizational objectives and the changing environment' (Phaal & Muller, 2009).

Roadmapping builds on and integrates many aspects of methods and tools applied in strategic planning and foresight for decades.[1] For instance, backcasting approaches, applied since the late 1970s (see e.g. Robinson, 1982; 1988), bear similarity to roadmapping (Weaver et al., 2000; Kok et al., 2011). Weaver et al. (2000) propose a strategic backcasting approach to developing research agendas and sustainable technology development. Kok et al. (2011) and (Quist et al., 2011) propose participatory backcasting approaches linked with scenario development. The deeper roots of roadmapping could be traced to the scholarship of pioneers of systemic approach to normative forecasting such as Erik Jantsch and Harold Linstone. In addition, a range of strategic technology programmes developed since the 1980s, were inspired by vision based collaborative technology policy making in Japan, the latest manifestation of which is the Strategic Roadmap for Hydrogen and Fuel Cells (Iida and Sakata, 2019).

Despite being associated with business and technology management studies, roadmap use permeates many topics, sectors, and organisational contexts. Roadmapping is used in a variety of planning and management practices, including product planning, service/capability planning, strategic planning, long-range planning, knowledge asset planning, program planning, and integration planning (Phaal et al., 2004). The roadmap format varies substantially depending on the application, it may be fully or partly text-based and include flowcharts, single- or multi-layer representations, bars, graphs or creative images to visualise the process (ibid: 15). There is no

[1] We are grateful to one reviewer for this point and reference suggestions.

Table 1
Dimensions and questions for STI roadmap assessment.

	Dimension definition	Roadmap assessment	Illustrative references
Descriptive analysis	1. Scope, purpose and objective(s) of STI roadmaps	1. What is the main rationale, purpose and scope of roadmaps? 2. What is the wider context in which roadmaps are developed?	Phaal et al. (2004) Phaal and Muller (2009) Ahlqvist et al. (2012) Carayannis et al. (2016)
	2. Portrayal of the future and description of how change occurs	1. How do roadmaps introduce visions, and pathways (e.g. narrative scenarios, targets, milestones, action plans)? 2. Do they discuss assumptions about probable futures and include narratives explaining how future change is expected to occur?	Phaal et al. (2004) Phaal and Muller (2009) Stirling, (2014; 2008) McDowall (2012)
	3. **Role of innovation:** The level of ambition and aspiration of innovation activities, including experimentation and system innovation. The extent to which roadmaps encourage innovation specialisation in areas relevant to sustainability transitions	1. What types of innovation activity roadmaps promote to enable sustainability transition? 2. What is the level of ambition of innovation? 3. Are roadmaps based on a strategic prioritisation process that includes existing and emerging areas of specialisation? 4. Do roadmaps aim at changing specialisation patterns to respond to sustainability challenges more effectively?	Ahlqvist et al. (2012) Carayannis et al. (2016) Mazzucato (2018) Schot and Steinmueller (2018) Kuhlmann and Rip (2018) Miedzinski et al. (2019)
Evaluative analysis	4. **Use of evidence:** The use of evidence and scientific knowledge to underpin the analysis, vision, pathways and action plans of roadmaps.	1. What types of evidence are used to inform the roadmapping process? 2. What is the overall quality of evidence base used for the exercise?	McDowall (2012) Miedzinski et al. (2019)
	5. **Alignment and credibility:** The extent to which roadmaps align actor strategy with the shared vision and engage actors in transformative innovation.	1. How are stakeholders selected, consulted and engaged at different phases of the roadmap process? 2. How inclusive is the roadmap process?	Phaal et al. (2004) Berkhout (2006) Borup et al. (2006) Phaal and Muller (2009) McDowall (2012) Konrad (2016)
	6. **Actionability:** The extent to which roadmaps are based on policy implementation capacity, and actor capacities in the innovation system.	1. What are the mechanisms of roadmap implementation? 2. Do roadmaps have their own dedicated action plans? 3. If yes, what is their status and actionability e.g. actions, budgets, responsibilities?	Ahlqvist et al. (2012) Carayannis et al. (2016) McDowall (2012) Miedzinski et al. (2019)
	7. **Coherence:** The extent to which roadmaps are embedded in and coherent with wider policy mixes.	1. How are roadmaps embedded into wider strategic framework and STI policy mixes?	Smits and Kuhlmann (2004) Wieczorek and Hekkert (2012) Ahlqvist et al. (2012) Carayannis et al. (2016) Miedzinski et al. (2019)
	8. **Learning and adaptability:** The extent to which roadmaps support on-going learning and allow adaptation of their elements.	1. How is the implementation of roadmaps monitored and evaluated?	Rotmans et al. (2001) Ahlqvist et al. (2012) Carayannis et al. (2016) Miedzinski et al. (2019) Van Mierlo et al. (2010)

(*continued on next page*)

Table 1 (*continued*)

Dimension definition	Roadmap assessment	Illustrative references
		Van Mierlo and Beers (2020)

single standard methodology or format template for the roadmapping process. It can involve many related techniques and approaches with different uses and formats.

The distinctive feature of roadmaps is that they offer a time-based framework to develop, represent and communicate, strategic plans in terms of the coevolution and development of technology, products and markets (ibid: 10). Roadmaps share a number of design features (Phaal et al., 2004; Phaal & Muller, 2009):

1. They include a reflection on the current state of development or a baseline i.e. 'where are we now?'.
2. They have an explicit purpose usually expressed as a vision and strategic priorities and targets i.e. 'where do we want to go?'.
3. They include an explicit perspective of time horizon and short-, medium- and long-term timelines that illustrate the process of getting to the vision i.e. 'how to get there?'.
4. Many roadmaps may present a path towards the vision by depicting various interrelated layers e.g. technology, product, sector, policy.
5. The development of roadmaps requires active stakeholder involvement from across disciplines, economic sectors, business and public organisations.
6. Irrespective of whether the process of roadmapping is intra- or inter-organisational, stakeholder discussions should be seen as a learning process and knowledge sharing exercise.

As a policy instrument, roadmaps have characteristics of procedural and substantive policy instruments (Howlett, 2019a, 2019b). Ahlqvist et al. (2012) consider innovation policy roadmaps as systemic policy instruments (Smits & Kuhlmann, 2004; Wieczorek & Hekkert, 2012) which integrate a variety of approaches to roadmapping and a systemic approach to innovation and technological change. Policy roadmaps have a dual role: they provide a systemic framework to facilitate policy design and implementation, and can directly influence shared expectations and subsequent behaviour of stakeholders engaged in STI processes (McDowall, 2012). This makes them well suited to address the systemic aspects of socio-technical transitions.

When innovators, entrepreneurs, scientists and other actors share clear expectations about a particular technology, the alignment of their activities towards shared goals makes technology development and diffusion more likely (Berkhout, 2006; Borup et al., 2006; Konrad, 2016; Rosenberg, 1976). The roadmap process is organised to actively raise actor expectations about a future STI path and drive them towards it (Konrad et al., 2016; McDowall, 2012). In this context, roadmapping can be seen as a mechanism for "governance of and by expectations" (Chen et al., 2007; Feindt & Weiland, 2018; Konrad, 2010; Voss et al., 2006; Voss & Bornemann, 2011). For example, as fuel cell technology did not live up to the initial optimistic expectations of actors, they subsequently shifted their expectations towards battery electric vehicles (Budde & Konrad, 2019).

There are other policy methods which are relevant to policy roadmapping oriented towards sustainability goals. For example, transition management is a multilevel model of governance that fosters co-evolution towards sustainability using visions, transition experiments and cycles of learning and adaptation (Rotmans et al., 2001; Loorbach, 2010). The focus on managing the transition process and the role of ongoing learning resembles policy roadmapping discussed in this paper.

2.2. *Assessment framework: roadmaps as a systemic policy tool*

The current literature explores the use of roadmaps in specific technology arenas. We build on literature to develop an assessment framework for roadmaps in the broader context of STI policy, but expand to the issues considered relevant to ensure that roadmaps can become a policy instrument that fosters system innovation (Ahlqvist et al., 2012; McDowall, 2012). The first three dimensions of our framework are descriptive, and their purpose is to capture the diversity of roadmapping approaches and contribute to the limited literature on the use of STI roadmaps to address sustainability challenges (Table 1). The descriptive dimensions are: (1) the scope and purpose of the roadmaps; (2) the way they portray the future; and (3) the way they convey an understanding of the role of innovation processes for roadmap goals.

The remaining five dimensions build directly on prior roadmap research in the context of STI policy (Ahlqvist et al., 2012; Carayannis et al., 2016; McDowall, 2012; Meissner et al., 2016). These evaluative dimensions focus on the extent to which roadmaps: (4) are based on evidence and scientific knowledge; (5) engage and align relevant stakeholders; (6) generate a clearly 'actionable' pathway or alternative pathways; (7) are used to facilitate policy coordination to ensure policy coherence; and (8) embed procedures for ongoing learning, evaluation, and adaptability. Table 1 lists the dimensions, lead questions and selected sources which guided the development of the analytical framework.

2.3. *Methodology*

The analysis is based on a critical assessment of 20 purposefully selected policy-relevant roadmap initiatives developed on the

Table 2
Comparison of descriptive features of the selected roadmaps.

Roadmaps	Roadmap purpose	Future Vision		Innovation pathways				Action plan	Baseline analysis
		Narrative vision	Targets	Structured Timelines	Targets & milestones	Narrative of change	Co-evolving layers		
1. SITRA. Leading the cycle. Finnish road map to a circular economy 2016-2025 (Finland)	Vision building; Stakeholder alignment Support for policy design and planning, Support for policy implementation	Yes	No	Yes	Yes (qualitative)	Yes	Yes	Yes	Yes
2. RISEnergy: Roadmaps for energy innovation 2030 (Sweden)	Vision building; Exploration of technology pathways; Technology advocacy	Yes	No	Yes	Yes	No	Yes	Yes	Yes
3. ERA Roadmap 2016-2020 (Norway)	Support for policy implementation	No	Yes	Yes	Yes	Yes	No	Yes	Yes
4. Roadmap to zero emissions for process industries (Norway)	Support for policy design and planning	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
5. Renewable Energy Roadmap (UK)	Support for policy design and planning; Support for policy implementation	Yes	Yes	Yes	Yes (qualitative)	Yes	No	Yes	Yes
6. Forest products industry technology roadmap (USA)	Technology advocacy	No	No	No	Yes	Yes	Yes	Yes	Yes (per tech)
7. Low Carbon Technology Plan (Japan)	Support for policy design and planning; Support for policy implementation	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8. Low Emissions Technology Roadmap (CSIRO, Australia)	Exploration of technology pathways; Support for policy design and planning	Yes	Yes	No	Yes (qualitative)	Yes	No	No	Yes
9. South Africa's Water RDI Roadmap: 2015-2025 (South Africa)	Stakeholder alignment; Support for policy design and planning	Yes	Yes	Yes	Yes	Yes	No	No	Yes
10. PowerAfrica: The Roadmap (USAID)	Support for policy implementation; Stakeholder alignment	Yes	Yes	Yes	Yes (qualitative)	Yes	Yes	No	Yes
11. TIFAC Technology Roadmap for Manufacturing (India)	Vision building; Exploration of technology pathways; Technology advocacy	Yes	No	Yes	No	No	Yes	No	Yes
12. National Energy Policy 2009-2030 (Jamaica)	Support for policy implementation	Yes	Yes	Yes	Yes (qualitative)	No	No	Yes	Yes
13. SET Plan (EU)	Support for policy design and planning; Support for policy implementation	Yes	Yes	Yes	Yes (qualitative)	Yes	Yes	Yes	Yes
14. SPIRE (EU) Roadmap	Technology advocacy	Yes	Yes	Yes	No	No	Yes	Yes	Yes
15. Roadmap to a Resource Efficient Europe (EU)	Vision building; Stakeholder alignment; Support for policy design and planning	Yes	No	No	Yes (mostly qualitative)	Yes	No	Yes	Yes
16. Science, Technology and Innovation Strategy for Africa 2024 (African Union)	Vision building; Stakeholder alignment; Support for policy design and planning	Yes	No	No	No (to be agreed at national level)	No	No	Yes	Yes
17. ASEAN Plan of Action on STI (APASTI) 2016-2025 (ASEAN)	Vision building; Stakeholder alignment; Support for policy design and planning	Yes	No	Yes	Yes	No	No	Yes	No
18. Carbon Capture and Storage in Industrial Applications (UNIDO/ IEA)	Vision building; Stakeholder alignment; Exploration of technology pathways; Support for policy design and planning	Yes	Yes	Yes	yes	Yes	No	Yes	Yes
19. ICC's Green Economy Roadmap (international NGO)	Vision building; Stakeholder alignment	Yes	No	No	No	Yes	Yes	No	No
20. WBCSD Vision 2050 (International NGO)	Vision building; Stakeholder alignment	Yes	No	No	Yes (qualitative)	No	Yes	No	No

national or international level that focus on areas relevant for sustainability transitions and the SDGs. We adopt a purposeful sampling strategy (Creswell & Poth, 2017) to collate a diverse sample of roadmaps that address sustainability objectives and span a wide variety of practical applications in policy processes. Our objective is not to compose a homogenous and representative or exhaustive sample. Instead, we set criteria directly linked to our research questions that allow us to select analytically relevant examples of what we want to study within the limits of available time and means (Cresswell and Poth, 2017).

The selection of cases was based on the following criteria: (1) reference to roadmap or related long-term strategic planning exercise which is interpreted as an intention to conduct a roadmap exercise; (2) focus on issues related to STI and sustainable development objectives at the national or international level; (3) direct or indirect relevance for public policy or shaping public policy agenda, and (4) longer time horizon of the strategic document with narrative vision or a quantitative targets. The selection produced the sample of 20 documents in Table 2. Table 2 overviews key characteristics of roadmaps related to the analytical dimensions of the study. The table was used by authors in the process of case selection for the analysis.

The co-author team developed the analytical framework of analysis and discussed it until there was consensus on its elements and its application to cases. Co-authors proposed various roadmaps and pre-selected them following a preliminary assessment based on the criteria (see Table 1). The team then analysed the texts of roadmaps and, if available, their background documents (e.g. evidence reports) and related policy schemes. The co-authors developed and filled in an excel table structured along the criteria with their observations and, when relevant, citations from the roadmap documents. The lead author provided an overall validity check by consulting the collected evidence and interpretations with each author and making sure the framework was applied consistently.

The cases exhibit considerable heterogeneity in the understanding and application of the roadmap concept. They are illustrative of how the word 'roadmap' in policy documents does not imply a standardised or uniform understanding or application of a roadmap technique. So, while some of the chosen documents are not titled 'roadmaps', they are included as they serve the same function with roadmaps, notably by featuring long-term visions and time-based pathways that illustrate how to reach a desired future state (e.g. 16. STI Strategy for Africa 2024). Section 3 proceeds with a detailed discussion along the dimensions defined in Table 1.

3. Analysis

In Section 3, we discuss the roadmap characteristics in eight subsections in terms of scope, future outlook, innovation, use of data, stakeholder alignment, actionability, coherence with other policies, as well as evaluation and policy learning

3.1. Scope and purpose of roadmaps

The analysis revealed a variety of objectives for policy roadmaps:

1. Development of long-term vision and agenda expressed as statements and images of desired and plausible futures (11. TIFAC 2035 Technology Vision (India), 19. ICC's Green Economy Roadmap).
2. Exploration and assessment of alternative innovation and technology pathways to achieve a vision, often expressed as scenarios (8. CSIRO, Australia).
3. Advocacy for technology and innovation to support technology areas, or specific technologies within specific areas, and research and innovation agendas with priority technology areas (16. SPIRE, EU; 6. Forest products industry roadmap, USA).
4. Alignment of stakeholders to support the vision and technology, innovation or policy pathways (19. ICC's Green Economy Roadmap; 6. Forest products industry technology roadmap, USA).
5. Support for policy design and planning of policy portfolios or programmes by elaborating selected technological and innovation pathways, often using milestones and quantitative targets (7. Japan's New Low Carbon Energy Plan; 13. EU SET-PLAN; 2. RISEnergy).
6. Support for policy implementation and management of ongoing policy programmes or other initiatives (10. Power Africa).

The roadmaps often address several of the above objectives with varying emphasis on two themes: technological innovation and sustainability (see Section 3.3). The choice of objectives and design of roadmap process depends on factors such as the capacity, competences and interests of stakeholders, and the maturity of the policy agenda on the national and international level, the stage of the relevant policy processes, and the alignment among local and international stakeholders.

Roadmaps that support strategies and policy instruments at early stages of policy design focus mainly on vision building, stakeholder alignment and technology advocacy, on-going or imminent political and policy shifts, agenda shifts, and major organisational changes (see Table 2 for an overview). For example, 15. Roadmap to a Resource Efficient Europe developed by the European Commission (EC) is heavily influenced by changes in the portfolio of Directorate General (DG) for Environment, the predominantly economic narrative of the Europe 2020 Strategy and the arrival of the new Commissioner (Miedzinski, 2015; Miedzinski et al., 2019). Due to changes in the political agenda and organisational setting the process focused on building a shared understanding, vision and stakeholder alignment within the EC, notably inside DG Environment and between DG Environment and DG GROW. The roadmap includes a broad narrative vision but has a weak focus on technology and innovation pathways.

In contrast, roadmaps that support more mature strategies and policy instruments at later stages of policy design, explore concrete technology pathways and support of policy design, planning and implementation (e.g. 5. UK's Renewable Energy Roadmap). Interestingly, roadmaps developed adjacent to on-going policy processes also focus on stakeholder alignment. For example, the roadmap developed to support the Power Africa programme (10 in Table 2) aims to reach out to stakeholders and promote the programme's approach to support its implementation.

The variety of roadmap uses for policy support reflects the variety of understandings about what a policy roadmap is. In some cases, roadmaps are implementation tools as in the innovation and technology management examples discussed above. However, roadmap techniques are routinely brought together under a roadmap umbrella with other strategic planning and foresight tools such as vision building, horizon scanning or scenarios. Policy roadmaps serve diverse functions that range from the construction of shared meanings and visions to project management and implementation. It appears, however, that the term 'roadmap' may have been appropriated by policy makers to describe various forms of strategic documents that attempt to bridge high-level visions and action plans.

3.2. Portrayal of the future

The analysis of roadmaps includes an assessment of how they depict the future and whether and how they address the questions "where do we want to go?" and "how to get there?". To do this we analyse three future-oriented components: a vision, a pathway (or multiple pathways) and an action plan. The roadmaps in the sample portray the future with three elements (Table 2):

3.2.1. Future vision

1. An expression of narrative vision as statement(s) or image(s).
2. Formal targets that are often quantitative.

3.2.2. Innovation pathways

1. Narrative of change (e.g. scenarios describing transition pathways and plausible causal mechanisms of change).
2. Intermediate targets and milestones to follow progress towards the vision (often with a structured timeline with short-, medium- and long-term horizons).
3. Analytical layers (or dimensions) of change.

3.2.3. Action plans

1. A set of short- and medium-term actions to make progress on identified pathways.
2. The frameworks and designs of the sample roadmaps differ substantially, so the emphasis they attach to each of the above elements tends to differ as well (see Fig. 1 for an illustration). They range from designs that resemble conventional technology roadmaps to hybrid designs with a mix of horizon scanning, broad visions, pathways and strategic planning elements. For example, 10. USAID is placed at the centre of the figure as it exhibits a balanced emphasis vision pathways and action plan relative to other roadmaps.

Future visions, pathways and action plans in the roadmaps are elaborated in diverse ways. The 'vision' may be expressed as a quantified target, such as the renewable energy target in the UK's renewable energy roadmap, or as a qualitative depiction of a desirable future state as in 15. Roadmap to a Resource Efficient Europe.

Similarly, the 'pathway' dimension differs in its emphasis. Some roadmaps emphasise specific technological milestones and developments such as cost or performance targets (e.g. 18. Technology Roadmap on CCS in Industrial Applications by UNIDO and IEA). These are the closest to classic 'technology roadmaps', setting out milestones and expectations for key developments in set timeframes. Other roadmaps are framed in terms of broader technology pathways that depict often quantified transitions of technological systems that meet the vision. These often draw heavily on techno-economic models (e.g. 8. Low Emissions Technology Roadmap by CSIRO in

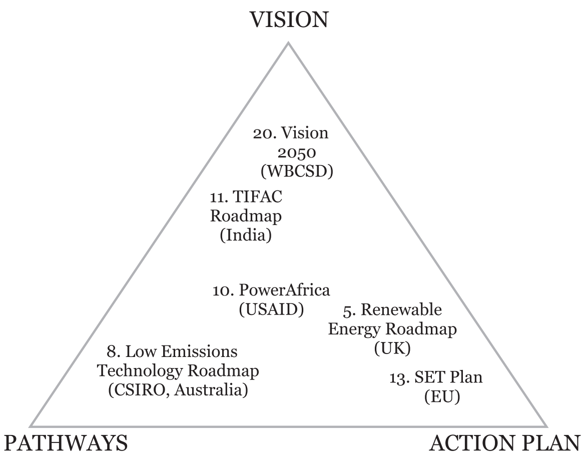

Fig. 1. Mapping policy roadmaps: blending visions, pathways and planning.

Australia). Still others are framed as broad narratives that encompass technological, political and other dimensions, with distinct public policy elements (e.g. 20. WBCSD's Vision 2050).

Pathways in the roadmaps that align closely with ongoing policy instruments typically reflect programme theories that underpin instruments they support or are even used to communicate and clarify the logic underpinning the programme (e.g. 10. Power Africa). Pathways reveal often implicit assumptions on how policy interventions are foreseen to trigger mechanisms of change depending on whether they have more of an innovation or sustainability logic (see Section 3.3). Pathways are highly relevant for sustainability transitions research and policies as they bring to the fore the underlying assumptions about how policy instruments are expected to deliver on SDGs (Rosenbloom, 2017). The lack of in-depth reflection on transition pathways is probably the most significant gap in most of the analysed roadmaps. Narratives of how transitions are expected to happen and more formal theories of change that explicitly discuss plausible mechanisms and dynamics of change are weakly articulated, left implicit or embodied in underlying quantitative models e.g. energy system models.

Finally, roadmaps differ in the way they articulate a future action plan. In some roadmaps produced by governments, plans are articulated as 'promises' – steps that leading actors are committed to take. But the 'planning' elements of roadmaps are often 'softer' with no specific commitments. For example, they can include recommended sets of actions with little sense that any actors feel compelled to implement them (e.g. 19. ICC's Green Economy Roadmap). There is diversity in whether plans are static, or whether there is a blending of the 'planning' element with the 'pathway', articulating steps that will/should be taken now versus those in the future.

3.3. Roadmap depiction of innovation and transitions to sustainability

In this section, we compare the level of ambition and aspiration of innovation activities roadmaps promote, including their role in experimentation and demonstration of system innovation.

Although roadmaps mention various innovation types, most documents focus on technological innovation, including new technologies, materials, and products. The focus on technology ranges from specific industrial technologies (e.g. 6. US Forest Products Industry Technology Roadmap) to a discussion on integrated technology systems (e.g. 7. Japan's New Low Carbon Technology Plan). These technology-oriented roadmaps embody a vision of the future that is determined by a techno-economic logic in which non-technological forms of innovation come second to the delivery of techno-economically optimal outcomes.

Nevertheless, several technology-oriented roadmaps acknowledge non-technological innovations as key for successful technology demonstration or diffusion. These innovations may include new business models seen as 'enablers' of technology diffusion in 8. CSIRO roadmap, or policy and institutional innovations that allow for adjustments in the energy market design in 6. UK Renewable Energy Roadmap.

Several roadmaps take a broad focus on technological and non-technological innovations to underpin wider transitions or specific projects. For example, 19. ICC's Green Economy Roadmap has a system-wide perspective on green economy transition which calls for economic, social and environmental innovations and regulatory changes. The Power Africa programme (10) focuses on concrete energy projects and demonstrates an integrated approach to innovation by promoting technology deployment and innovations in finance, organization of utilities and public sector, policy and regulatory frameworks. The programme's model considers the importance of physical infrastructure (power plants and grids) and institutional infrastructure (institutional capacity, policies, and regulatory framework) to manage the energy system transition towards renewables.

All roadmaps have a high level of ambition in terms of innovation support. The ambition may be the introduction of technological innovations or new collaborations and innovative governance models to mobilise various actors. For example, 11. TIFAC's Technology Vision calls for 'National Missions' that should rely on innovative governance modes and implementation paths: "(…) these projects require circumventing bureaucracy and standard operating procedures [and] they also involve specific targets, have a defined timeline, possess a clear inventory of resources and constraints and require only a few (or single) carefully identified players." (p. 98). TIFAC's manufacturing roadmap elaborates on this vision but it does not introduce clear targets and milestones to make this vision more realistic and does not come with clear information on the follow up. This suggests a possible gap between the ambitious levels of desired innovation and the capacity to implement the roadmaps.

An interesting dimension in some roadmaps is the explicit consideration of perceived risk in the innovation process. For example, 11. TIFAC's Technology Vision considers perceived risk as part of an innovation ecosystem. The approach of 10. Power Africa programme to risk management and mitigation focuses on support of 'first-of-their-kind' energy projects to 'de-risk' future similar projects. This is a rational model which assumes that lessons learned from projects implemented in specific social, economic and cultural context can be effectively shared and applied in other contexts. In contrast, the 14. SPIRE roadmap frames risk mainly from a market failure perspective, where the main risk sources lie in the uncertain nature of long-term investments in complex innovative projects. In this respect, the roadmap emphasises the role of public-private collaboration and risk sharing in carrying out high-risk projects.

With their high ambitions, these roadmaps devote little attention to the risks and uncertainties inherent in systemic transformative changes. The documents frame risk as something manageable and controllable much in the spirit of a technology management technique. None reflects in depth on what to do if risks of planned investments or regulations cannot be fully assessed and managed or even anticipated due to inherent uncertainties of system innovation, and how to revisit and revise initial plans if demonstration activities fail or create undesired rebound effects.

In our assessment we also analyse the extent to which roadmaps encourage innovation specialisation in the areas particularly relevant for sustainability transitions. One the one hand, roadmaps that implement current policy strategies and programmes simply reflect their priorities and specialisation choices. For example, they focus on preselected technology and innovation areas such as 37 low carbon technologies in 7. Low Carbon Technology Plan for Japan.

On the other hand, several roadmaps incorporate a dedicated process to prioritise key technology and innovation areas (e.g. 5. UK Renewable Energy Roadmap, 8. CSIRO's Low Emissions Technology Roadmap, 2. RISEnergy). For example, the government-led UK Renewable Energy Roadmap selects eight priority technologies expected to contribute the most towards its 2020 target. The prioritization is based on commissioned modelling work and evidence. Similarly, 8. CSIRO's Low Emissions Technology Roadmap concerns the strategic prioritization of technologies, capabilities and deployment opportunities, in the Australian context. The process is informed by energy system modelling combined with stakeholder consultation.

In contrast, roadmaps that focus on vision building and technology advocacy most often do not prioritise specific technology and innovation areas. Instead, they list many relevant technology and innovation options relevant for the main challenge or sector (e.g. 11. TIFAC's Technology Vision in India or shift to a green economy in ICC's roadmap). Much as in a technology advocacy approach, business-led sectoral roadmaps addressed to policy makers come up with long lists of priorities and technology areas reflecting diverse needs and interests of the involved sectors (e.g. 14. SPIRE, 6. US Forest Products Technology Roadmap).

In summary, the role of roadmapping with respect to strategic specialisation appears to depend on its embeddedness in the ongoing policy processes. Roadmaps are either applied as implementation tools for choices already made or they are combined with other strategic planning and foresight tools as part of the broader process of design, selection and strategic prioritization of technology and innovation areas.

3.4. *Use of evidence and scientific knowledge*

We evaluate the roadmaps to understand how current evidence and scientific knowledge is used to underpin their baseline analysis, vision, pathways and action plans. The use of evidence and scientific knowledge ranges from a very selective use of mainly secondary evidence to robust designs based on mixed methods approaches including the use of primary and secondary data. Table 3 lists the use of primary and secondary data and evidence in the sample roadmaps.

All roadmaps include references to secondary evidence and at least allude to expert and stakeholder consultations. In terms of secondary evidence, the roadmaps with a selective evidence base refer to broadly accepted and credible sources, often reports from international organisations, for instance, references to IEA's reports in 7. Low Carbon Technology Roadmap for Japan.

Several roadmaps include an extensive dedicated evidence base that relies on primary and secondary data and diverse evidence sources (see 1. Finish Circular Economy Roadmap; 13. EU SET-PLAN or 15. Roadmap to a Resource Efficient Europe). For example, 1. the Finnish roadmap for a circular economy is based on a literature review and an extensive consultation of over 1000 stakeholders. The stakeholders include companies, trade unions, research organisations, environmental organisations, consumers as well as various ministries (Environment, Agriculture and Forestry, Economic Affairs and Employment). For example, 11. TIFAC's roadmap on future prospects and technologies in manufacturing is based on interviews and around 100 responses to a survey sent to around 600 professionals across India.

The roadmap designs in the sample serve different purposes and reflect the diverse contexts in which they were developed and implemented. Nevertheless, our assessment allows for three critical observations on the quality of evidence base of roadmaps. First, the scope of evidence base in most roadmaps has a predominantly techno-economic perspective on sustainability transitions. For example, 8. CSIRO's roadmap on low-carbon technologies used a model-based approach with techno-economic optimisation based on net costs to consider technology options, with little consideration of broader considerations related to social equity, feasibility and other non-cost values.

Second, only few roadmaps include a transparent research design and methodology (e.g. 8. CSIRO). Most analysed roadmaps have short descriptions of methodology and do not include clear references to all evidence used in the document. Many documents do not specify whether they benefit from any independent peer review or other unbiased quality assurance measures to ensure the quality of evidence base.

Finally, in several cases it is difficult to analyse the robustness of the evidence base underpinning roadmaps. Many roadmaps, especially the industry-led processes, rely fully or partly on business data which is not always fully accessible or peer reviewed, and, therefore, their quality cannot be easily assessed (e.g. 13. SET PLAN Norway's Roadmap for the process industries). In some cases, this

Table 3
The use of secondary and primary data in roadmap design process.

	Selective primary data collection and stakeholder engagement	*Extensive primary data collection and stakeholder engagement*
Extensive use of literature and secondary data	5. Renewable Energy Roadmap, UK	1. Circular Economy Roadmap, Finland
	8. Low Emissions Technology, Australia	11. TIFAC, India
	10. Power Africa Roadmap (extensive use of internal programme monitoring data)	3. EU SET-PLAN
		15. EU Resource Efficiency roadmap
Selective use of literature and secondary data	7. Low Carbon Technology, Japan	6. US Forest products industry, US
	3. Norwegian ERA Roadmap	14. SPIRE, EU
	2. RISEnergy, Sweden	9. Water RDI roadmap, South Africa
	17. ASEAN APASTI	16. STISA, African Union
	19. ICC Green Economy Roadmap	18 UNIDO Carbon Capture and Storage
	10. USAID PowerAfrica: The Roadmap.	20. WBCSD (2010). Vision 2050

limitation is acknowledged in the roadmap document. For example, the EC was reluctant to endorse the technology penetration targets proposed by the industry sectors for the EU's SET PLAN as the Commission could not corroborate the underpinning data.

3.5. Stakeholder alignment

Alignment is key in sustainability transitions as it enables innovations to enter mainstream markets and compete with dominant solutions backed by incumbents (Geels & Schot, 2007). In considering this criterion, we look at the actions taken to create stakeholder alignment in the roadmap development process, and the extent to which the roadmap content is based on and reflects stakeholder alignment.

The roadmaps present a spectrum of stakeholder engagement, from direct engagement and ownership to arm's length consultation. Most roadmaps feature involvement from stakeholders across this spectrum. Multiple factors appear to impact how many stakeholders are able to 'own' a given roadmap and its contents. In many cases, the limited, consultative engagement of stakeholders beyond the authors is by design (e.g. 8. CSIRO, 11. TIFAC, 5. UK's RER). In some cases the author group consists of stakeholders, and consultation beyond it is likely limited as a practical concern (e.g. 13. EU SET Plan). In other cases, the roadmap itself represents an explicit attempt to align stakeholders not otherwise connected by a relevant institutional framework (e.g. 6. US Forest Products Roadmap).

The extent to which the roadmaps evince actual alignment between stakeholder strategies also appears to vary with the extent of direct consequences the roadmap has for the stakeholders. The engagement of donor institutions in the Power Africa Roadmap and of research institutes and companies in the 14. SPIRE and 6. US Forest Products Roadmaps likely reflects direct financial implications of the recommendations developed therein. There may also be a trade-off between alignment and novelty. Alignment between stakeholder positions is more explicit where roadmaps focus on existing programmes and initiatives (e.g. 10. USAID's Power Africa, 14. SPIRE, 3. ERA roadmap in Norway). Where roadmaps ask stakeholders to embrace novel views or positions, the degree of alignment is less clear and likely limited to a smaller group of actors.

3.6. Actionability

The roadmaps authored by public authorities often include action plans, though the analysis of feasibility and implementation capacity is often generic, and lacks the specificity of, for example, ex-ante evaluations or impact assessments conducted for specific programmes or instruments.

In private-sector and research-driven roadmaps, actions relevant to policy seem to come in the form of a request from one stakeholder group to another e.g. industry to government or civil society to industry. In these cases, actionability becomes a problematic framing; the proposals in these roadmaps can be seen as part of a societal negotiation rather than as guidelines for action. For example, 14. SPIRE and 6. US Forest Products roadmap develop research agendas. In this sense they are also 'negotiation' roadmaps, but when attached successfully to a public research programme as was the case with 14. SPIRE, they can become highly and specifically actionable.

The 10. Power Africa Roadmap is notable in this regard, as the process and document seek to support and strengthen (trans)actions already underway on the ground, and to align them with a long-term development/transition pathway, rather than to identify and initiate these (trans)actions. The roadmap is almost entirely concerned with actionability and implementation capacity.

3.7. Coherence with wider policy

The coherence criterion considers whether and how well the roadmaps relate to wider STI policy mixes, sustainability strategies, policies and the SDGs. Policy mix coherence is key in fostering sustainability transitions (Kern et al., 2019; Rogge & Reichardt, 2016).

Our assessment suggests policy roadmaps tend to inherit their relation to superordinate strategies and policies from their immediate institutional context. Thus, a roadmap authored by a government department will refer to the politically established goals for its area of authority and an industry will refer to policy targets or objectives relevant to its activities. This approach simplifies and supports a direct correspondence between important policies and roadmaps. However, it can also create blind spots, particularly where systemic innovation is essential. The Norwegian ERA roadmap (3) is highly specific and tightly prescribed by the ERA process but is virtually silent on sustainability goals or policies in Norway, EU, or globally. The WBCSD's Vision 2050 (20) is deeply rooted in global sustainability objectives, but perhaps inevitably remains disconnected from the national policy contexts that will be crucial for driving private sector action. An exception is Japan's low-carbon technology plan, which highlights the policy-market dynamics and domestic-transnational considerations as essential to implementation.

3.8. Evaluation, learning and adaptability

A key feature of classic technology roadmaps is their enabling role in progress monitoring towards targets. These roadmaps also typically allow for revisions of pathways and milestones. Our assessment considers the extent to which they support on-going learning and whether they include mechanisms that allow for adaptation based on new evidence. Whilst some of the roadmaps include commitments for monitoring progress, for example, 5. UK Renewable Energy roadmap, we find relatively little focus on the process of learning and adaptation.

Roadmaps that support existing programmes and strategies tend to rely on the systems set up for these programmes for monitoring and evaluation. This appears to be sufficient, but roadmaps for sustainability challenges often cover time horizons that stretch beyond formal programme duration so that exclusive reliance on programme's own monitoring data may be insufficient. Most of the roadmaps make only generic or no provisions for their review and adaptation. Several roadmaps invite stakeholder feedback and commit to regular revisions but rarely deliver fully on them despite explicit commitments. For example, UK Renewable Energy roadmap (5) had only two annual updates following its formulation in 2011, or – at the time of analysis - we did not find evidence of any systematic follow-up of 14. SPIRE or 19. ICC Green Economy Roadmap.

The roadmaps offer good examples of monitoring and evaluation. For example, the Power Africa roadmap (10) applies an evidence-based approach to making assumptions about reaching quantitative targets based on an analysis of lead times or time lags in finance and construction of renewable energy projects. The expected progress of Power Africa projects is then estimated for 2020, 2025 and 2030, allowing for adjustments in assumptions and the support model in light of observed progress in project implementation. Importantly, the roadmap document does not introduce new targets but is designed to explain how the targets introduced by its parent programme can be met. The programme is based on the learning-by-doing approach where lessons learnt during implementation are used to add country- and technology- specific advice. However, the roadmap does not detail how lessons learnt and evidence collected during the implementation can be used to prevent or learn from future project failures.

In summary, most of the roadmap processes have not created learning environments and reflexive governance (Smith et al., 2010; Voss et al., 2006) that would enable pathway adaptation in response to unexpected outcomes, including failures or unexpected successes and changing context. In order to create a learning environment, roadmaps should be designed as an on-going policy learning process (Ahlqvist et al., 2012) rather than a one-off, isolated exercise, as is often the case.

4. Discussion

In this section we discuss how policy relevant roadmaps can support the design and implementation of STI policies that contribute to transitions towards long-term sustainability goals. Drawing on the common characteristics of the roadmaps we assessed, we argue that to address sustainability issues policy roadmaps should integrate three future-oriented dimensions: visions, alternative pathways and plans (Fig. 2). Processes positioned at the extremes of the triangle might not be considered 'real' roadmaps or at least, they do not exploit fully their potential. It is the integration of different dimensions that distinguishes a policy roadmap from a purely exploratory scenario exercise (vision and pathways); a strategic plan (planning only, or plan and vision); or a vision (shared vision or multiplicity of congruent visions[2]).

Integration of these three dimensions in the roadmap process is a challenge but policy roadmaps that focus on transitions should embrace and manage the inevitable tensions that arise between different ways of engaging with the future. Furthermore, roadmap design should allow for iterations between these dimensions. To tap into the potential of the process, STI roadmaps can benefit from the use of various tools and methods selected to meet specific objectives and visions. For example, roadmaps are one of the many available tools to be considered in transition analyses (Boons et al., 2021; Geels et al., 2016; Holtz et al., 2015; Köhler et al., 2018; Papachristos, 2019, 2018, 2014, 2012, 2011; Papachristos & Adamides, 2016).

Embracing the plurality of transition pathways in roadmaps may lead to tensions between non-committal exploration of alternative transition pathways and committal processes of prioritisation and action plan. How STI policy roadmaps reconciliate strategic prioritisation with the existence of alternative transition pathways? Stirling (Stirling, 2014) argues for "emancipating transformation' by ensuring variety: "hopes for genuinely progressive 'green transformations' are not about fear-driven technical compliance, but hope-inspired democratic struggle and choice". Sustainability transitions require a variety of innovations and technologies to be tested and experimented with in various contexts (Steward, 2008).

Moreover, can roadmaps as policy instruments support a variety of innovation pathways? The roadmaps in this paper display a tension between 'opening up' to acknowledge and foster multiple possible pathways and acknowledging deep uncertainty, and 'closure' i.e. commitment to a narrowly defined single view of the future and playing down uncertainties (Stirling, 2014, 2008). In the context of technology roadmaps, closure implies that a prescriptive roadmap is developed on the basis of a consensus of a subset of relevant, more powerful and influential actors (McDowall, 2012). However, this closure is likely to reflect incumbent interests, tied up with a less-sustainable socio-technical system that focuses narrowly on what can and will be done. Thus, early closure is likely to downplay the importance of uncertainties and alternatives pathways.

Roadmaps produced by public policy organisations should be expected to be particularly sensitive to diverse interests, visions and implementation needs. Roadmaps that promote a broad strategic vision should acknowledge uncertainty, the diversity of possible pathways, and avoid excessive closure. Roadmaps for the implementation of a specific programme, or the development of a specific sector or technology, should be based on a wide strategic framework that acknowledges uncertainty and plural pathways ("opening-up" context), but should themselves become a strategic framework that will foster an informed and politically acceptable selection and co-design of single or several specific pathways to be pursued ("closing down").

In the context of sustainability transitions, which require a strong directionality (Smith et al., 2005), opening up and closure could be part of the same roadmapping framework or process. This would compensate for the limited link of roadmaps to experimentation. For example, an STI roadmap could cover programmes to allow design and experimentation with *alternative* innovations in various regions. Policy makers and stakeholders could draw lessons learned from these situated experiments, and adapt the roadmap to focus on the most promising pathways or try new alternatives in case of failure. In this approach, prioritisation is a deliberative *process* based

[2] Multiple visions are possible too, and reference to vision congruence rather than shared visions, provides more flexibility. We thank one of the reviewers for clarification on this point.

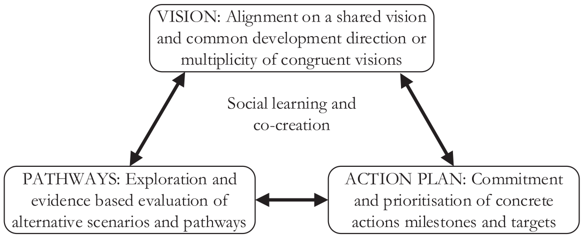

Fig. 2. Policy roadmap as a strategic blend of visions, pathways and planning.

on learning from experiments. STI roadmaps for sustainable transitions could benefit from lessons learned in programmes that encourage experimentation with a view to introduce good practices in mainstream policy support e.g. Regional Programmes of Innovative Actions co-funded by the EU Structural Funds.

A challenge for STI policy roadmaps is to embrace the complexity and uncertainty inherent in sustainability transitions and system innovations (Altenburg & Pegels, 2012; Geels, 2005; Kemp et al., 1998). Our analysis reveals that roadmaps pay limited attention to risks and uncertainties and rarely elaborate on how to address and manage those that relate to innovation and technology areas. The reference to risk is frequent but overly generic e.g. the need to share risk between private and public sector in 16. SPIRE. This opens up possibilities to undermine well-intended policy statements to minimise risk, seek consensus, foster trust to enable participation or promote responsibility, and it also opens up collective capacities to hold open, progressive, plural, critical political discourse (Stirling, 2014).

Most of the roadmaps do not include dedicated mechanisms to evaluate progress, learn from it, and adapt the chosen pathways or milestones. Adaptability is a key roadmap feature that allows response to problems and appropriate action when implementation issues or changes arise. Roadmap adaptability depends on the ability to learn throughout the implementation process, which is facilitated by well-designed monitoring and evaluation systems. STI roadmaps for sustainable development, that comprise processes and initiatives far more risky and complex than most technology roadmaps, could include a reflexive component on the nature of risks, and explicit mechanisms to anticipate and adapt their approach in case of failures, unexpected success or significant changes in the context.

STI roadmaps alone are clearly no panacea for the systemic shortcomings and failings of policy processes, but they could be used to help reframe the discourse on risk, uncertainty and failure with an increased focus on transformative innovation and stronger emphasis on learning and adaptability. For example, the development of alternative innovation pathways towards the SDGs can help to assess and compare the risks and uncertainties of these alternatives. Pathways can also help to assess distributional impacts and identify potential 'winners and losers' of alternative technology and innovation choices. This comparison can help to choose more resilient policy options and better inform decisions to invest in risky innovation projects.

A final cautionary remark is in order on the limitations of this study. Our discussion draws on our assessment and reflection on the purposefully selected 20 roadmaps. This approach allows us to discuss different ways that policy relevant roadmaps are approached by policy makers in different contexts. It provides us with relevant insights to make a contribution on the design and implementation of STI roadmaps that can contribute to transitions towards long-term sustainability goals. A systematic review study, however, would need to cover a greater variety of policy roadmapping exercises complemented with empirical evidence wand allow for more fundamental, impactful or even radically different findings than featured in this section.

5. Conclusion

This paper shows that STI policy roadmaps are used in diverse ways that range from support of strategic stakeholder alignment to programme implementation. Roadmaps have the potential to become a versatile systemic policy instrument to ensure strong directionality and temporal coherence of policy mixes. Policy roadmaps, we argue, can bridge short-term action plans and long-term visions by integrating the exploration of alternative innovation pathways in the roadmapping framework. Because of their adaptability to diverse applications, roadmaps have the potential to become a versatile systemic instrument for policy, that would be useful for sociotechnical transitions as well.

Roadmap development can be done in a wide variety of ways. Not all of them are useful, and some embody rather narrow views of the future that fail to represent the diverse perspectives, interests and the scale of systemic uncertainties involved in sustainability transitions. While evidence supports the usefulness of roadmaps across a number of governance processes, and the overlap with transition process characteristics may be appealing, our assessment suggests that the roadmaps exhibit the following characteristics:

- Weak follow-up: failure to bridge vision with action (inherent problem of foresight).
- Weak embeddedness in a wider policy mix.
- Weak reflection on stakeholder engagement and governance of the roadmapping process.
- Limited focus on experimentation e.g. testing pathways.
- Weak reflection on theories of change in pathways.
- Limited attention to risks and uncertainties.

- Limited focus on evaluation, learning and adaptability.

Far from being exhaustive this paper indicates key knowledge gaps and issues for further research and attention if the current weaknesses are to be overcome. In light of the current resurgence of interest among policy audiences for STI roadmapping to support SDGs, there is a clear need to build a richer body of knowledge on roadmapping as policy instrument for sustainability transitions. This knowledge is important to ensure that roadmapping becomes a strategic framework to promote transformative change rather than simply a vehicle to reproduce incumbent socio-technical systems and structures. Such transformative policy roadmapping should embrace complexity and uncertainty, open up policy design to consider alternative innovation pathways, and provide a framework to monitor and learn from experiments and demonstration projects that test various pathways.

Appendix A. Roadmap documents

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2. RISE (2016). RISEnergy: Roadmaps for energy innovation in Sweden through 2030. Research Institutes of Sweden.
3. Ministry of Education and Research of Norway (2017). Norwegian ERA Roadmap 2016-2020. Norway.
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