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Technology roadmaps for transition management: The case of hydrogen energy

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ABSTRACT

Technology roadmaps are increasingly used by governments to inform and promote technological transitions, such as a transition to a hydrogen energy system. This paper develops a framework for understanding how current roadmapping practice relates to emerging theories of the governance of systems innovation. In applying this framework to a case study of hydrogen roadmaps, the paper finds that roadmapping for transitions needs to place greater emphasis on ensuring good quality and transparent analytic and participatory procedures. To be most useful, roadmaps should be embedded within institutional structures that enable the incorporation of learning and re-evaluation, but in practice most transition roadmaps are one-off exercises.

1. Introduction: roadmaps, transitions and hydrogen

Technology roadmaps have become ubiquitous in discussions of long term energy technology policy. Indeed, technology roadmapping has found a place at the heart of global policy efforts for a low-carbon future: In 2008, the G8 and Major Economies declared "We also note the value of technology roadmaps as tools to promote continuous investment and cooperation in clean energy research, development, demonstration, and deployment." [1].

Increasingly, technology roadmaps are developed for major socio-technical systems changes, or technological transitions. This paper examines the role of technology roadmaps as instruments in the governance of such long-term transitions. To do this, it draws on a large literature on socio-technical change that has developed over recent years, but that has done so largely independently of the literature on roadmapping. This paper seeks to bring together these separate but related strands of research, and make recommendations for the practice of roadmapping in transition policy.

To illustrate and inform the theoretical discussion, the paper draws on a case study of hydrogen roadmaps. Hydrogen energy – a long-term and highly uncertain option for enabling deep decarbonisation of the energy system – has been a particular focus for government-directed roadmapping activities. This paper draws on a review of hydrogen roadmaps to present a critical analysis of the use of technology roadmapping as part of the 'toolbox' of policy-makers tasked with steering society towards a low-carbon future.

The paper is structured as follows. Section 1 introduces technology roadmapping, and describes the way in which roadmaps have been adopted by policymakers seeking to facilitate transitions towards alternative, more sustainable, technological systems. Section 2 draws on insights from socio-technical theory to illustrate how roadmaps can be used as tools in governance of transitions, and uses this literature to develop a framework for evaluating roadmaps in Section 3. Section 4 introduces the case study, hydrogen energy. Section 5 evaluates hydrogen energy roadmaps against the framework developed in Section 3, and Section 6 draws conclusions.

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2. Technology roadmapping

2.1. Technology roadmapping: origins and use in industry

Technology roadmapping as a technique was brought to prominence in the academic literature by Galvin [2], in an editorial in *Science* that highlighted the successful use of roadmapping at Motorola and in the semi-conductor industry. Since then, a large literature has developed dealing with technology roadmapping in industry and within firms [3–7]. The approach has become widespread, and can be seen as part of the ongoing trend for technology futures to be more actively organized and managed both by private and public organisations [8].

Technology roadmaps allow technology developments to be integrated with business planning, and they allow assessment of the impacts of new technologies and market developments on the prospects for a firm [5]. Roadmaps are developed in a number of ways, and various scholars have produced outlines of the key stages of developing technology roadmaps (for excellent overviews, see [4,5]). From this variety of approaches, a set of core practices can be identified:

- Roadmaps identify the major players in the innovation system, and provide an outline of the industry or emerging innovation network.
- They describe the current status of a technology.
- They set out a view of the future of a technology, including the possibilities for its development and deployment.
- They identify needs and priorities—including R&D needs, and sometimes market and regulatory needs, such as codes and standards.
- Those produced at the sectoral level (rather than by individual firms) aim to offer a consensus view of the way forward. As a result, they are almost always collaborative, or at least consultative, in the sense that they include the views of different teams, groups and stakeholders.
- They are frequently – but not always – depicted graphically [9].
- Many roadmaps – but by no means all – involve regular updates and monitoring of progress against milestones and targets. The roadmap developed by the semi-conductor industry is re-issued every 2 years, with 'updates' issued in the interim. It, and roadmaps like it, is continually redrawn to reflect new knowledge and developments.

Roadmaps should not be understood as projections or forecasts. Rather, roadmaps conflate and combine three different ways of understanding the future: expectations (what is thought likely to happen), desires (what is hoped will happen) and promises (what will be made to happen). In combining and conflating these perspectives, roadmaps weave a picture of the future that attempts to galvanise actions in the present. In doing so, roadmapping processes often draw on other foresight approaches, including scenarios, Delphi surveys, and quantitative forecasts. In effect, we can understand roadmaps in the following ways:

– As the current 'state of the debate'. A roadmap embodies a view of the status of a technology in terms of its development, and an inventory of possibilities, barriers and opportunities. This is usually presented as a consensus view, at least of those who have participated in the process.
– As an attempt to create a *realistic and pragmatic projection* of what is both feasible and desirable. Roadmaps are informed by analysis, and aim to set out a plausible view of what the future could hold. A successful roadmap must be seen as at least credible or plausible, even if they are not always seen as setting out a likely or inevitable future.
– As *a guide to innovators*. A roadmap maps the key areas in which progress is required (what Hughes [10] memorably described as 'reverse salients'), including the barriers and the opportunities, allowing scientists and engineers to get a clearer sense of where resources need to be focused to move the innovation system forwards.
– As a 'bid' for a particular future in a competitive market in which only some futures will attract resources and support. Roadmaps articulate a particular view of what the future can and should be like – i.e. they set out a normative vision of the future – and they demand resources and support accordingly [11]. As a result, we should expect roadmaps to be optimistic, and sometimes even hyperbolic.
– As a *promise* of what will be done, and how the future will unfold.
– As a *process* that facilitates the development of networks and the alignment of actors within an innovation system.
– As a *tool* in the ongoing management of innovation. Many roadmaps are periodically updated, and provide an institutional structure through which actors in the innovation system can monitor progress, consider changing priorities and identify opportunities.

2.2. Roadmapping in public policy: from products to systems

Technology roadmapping was first applied at the level of individual products and technologies. Over time, the scope of roadmaps has expanded to encompass product or technology groups, and whole industry sectors [12]. As the scope of roadmapping has expanded, governments have become more involved in using roadmaps in public policy. Early examples of governments supporting technology roadmap initiatives emerged from industry and trade departments, keen to foster the competitiveness of their industries [13,14]. In these exercises, the role of government was limited to providing support for the roadmapping process, and government was not necessarily interested in the direction taken by the technological developments discussed. The interest of government in promoting roadmaps was to facilitate the development of competitive industries, and to push science and technology forward, wherever forward might be.

More recently, roadmaps have become a tool by which governments foster not only the development of competitive industries, but also the development of new and emerging technological systems that meet social goals, such as low-carbon technologies. Roadmaps are developed as part of the process of setting directions for the socio-technical development of society. The last decade in particular has seen increasing use of roadmapping approaches in technology policy by governments, particularly in the context of energy policy and the transition to a low-carbon energy system [15].

In making this shift from industry to public policy, the nature of technology roadmapping activities has adapted to include a broader set of concerns. Technology roadmapping in industry tends to focus on relatively short term and quite technical developments (see, for example, the roadmaps produced by the semi-conductor industry [16], which are often cited as an archetype of successful roadmapping). In contrast, governments and policy advocates have tended to use the tools, approaches and language of technology roadmapping to address issues that are considerably longer-term in nature [15], and that involve substantial social and political as well as technical elements.

This broadening of the scope of roadmapping activities echoes a shift in technology policy for the environment, from the promotion of individual 'environmental' technologies (such as end-of-pipe scrubbers), to the transformation of entire socio-technical systems [17,18]. Roadmaps, once used to map out the development path for new products, are now developed to articulate pathways for long-term sustainable "systems innovations" or "technological transitions" (these terms are used as described by e.g. [19,20]). In other words, they are used to articulate a vision of the development of an entire system, including the infrastructural, market, policy, educational and regulatory developments as well as technological issues.

The potential development of a 'hydrogen economy' is one such example—the development of a hydrogen energy system requires substantial shifts in institutions, physical infrastructure, user behaviour, supply chains, industry structure and so on. It is not simply the development of a set of new technologies, but rather it is a socio-technical transition [21]. Roadmaps for a hydrogen economy encompass a much broader array of concerns than is typical in technology roadmaps in industry.

In short, technology policy makers and advocates interested in the governance of technological transitions have adopted an analytical and management tool that was developed for use within industry (technology roadmapping), and transferred it into a new context (socio-technical transitions). Governments are using roadmapping as one of a number of tools (along with fiscal structures, technology funds, trading schemes and traditional regulations) for managing – or attempting to manage – long term transitions in the socio-technical arrangements of society.

This shift raises questions about the way in which the tools of technology roadmapping can be applied to these broader, more systemic shifts in socio-technical arrangements.

3. Technology roadmaps as instruments of transition policy

Policy-makers are already using roadmaps as part of the policy architecture through which they attempt to steer transitions towards more sustainable socio-technical arrangements. However, the practice and literature on roadmapping, and the literature on the governance of transitions, have developed largely separately. In this section, the paper seeks position 'transition roadmaps' within the broader theoretical literature on the governance of transitions.

3.1. Governing transitions: insights from socio-technical theory and transition management

Within the socio-technical literature, technologies are understood to be embedded within broad configurations – 'seamless webs' – of social and technical arrangements [10,20,22]. These arrangements include patterns of behaviour, social norms, regulatory rules, and so on. These structures in which technologies are embedded are termed a socio-technical 'regime', or 'technology-specific innovation system' [23]. Regimes are dynamically stable and resist change, resulting in inertia and what is often called 'lock-in' [24,25].

Change in such systems can be best understood through an evolutionary perspective [20,26]. Emerging technologies are developed and nurtured in niches, by 'proto' innovation systems. In the early stages of development, the actors involved in the emerging innovation system are less closely aligned than those in mature systems. To develop, networks of actors must align and coordinate action, and fulfil a series of key activities or 'functions' of a successful innovation system, including: development of knowledge, entrepreneurship, mobilization of resources, legitimation, guidance of the search, and diffusion of knowledge through networks [27,28].

This model of technological change as a quasi-evolutionary process, in which action is constrained by regimes, provides an explanation for the frequently observed failure of technology policies that are based on classic market failure approaches [27,29]. The economics of innovation (see, e.g. [30]), on which such policies are based, can be seen as only a partial account of the dynamics of innovation, because it does not take into account the 'embeddedness' of technologies within complex social structures that constrain action.

Advocates of market-based approaches to innovation policy frequently contrast market-based policies with the perceived alternative: top-down planning and control, characterised by a strong role for the state in attempting to 'pick technological winners' [31]. Quite rightly, attempts to plan technological progress are seen with considerable scepticism: we do not and cannot know which frontiers of scientific and technical advance will lead to the most rapid progress. Technological developments are inherently unpredictable and indeterminate. Furthermore, given the nature of innovation systems as networks of actors, practices and institutions, it is clear that no-one actor is 'in charge' to do the top-down planning [32]. The power required to steer the socio-technical development is diffused through networks of actors, rather than held by the state or by any one actor. As a result, attempts to 'plan' a successful transition are likely to fail [33], as are attempts to re-make socio-technical arrangements entirely through price signals.

How, then, can governments guide the emergence of more sustainable socio-technical systems? Various approaches have been suggested that emphasise a 'reflexive' and adaptive approach, focusing on learning, reappraisal and experimentation. These echo adaptive management approaches adopted in natural resource management [34,35], and include transition management [36,37], strategic niche management [38], and time strategies [39,40]. The literature on network governance is also useful here, describing governance strategies when power is diffused through actors in heterogeneous networks [41], of which emerging innovation systems are an example.

Of greatest relevance to our understanding of roadmaps as governance tools for transitions is the attention that the socio-technical literature in general, and transition management in particular, has placed on the role of expectations and futures in guiding socio-technical change. In order to more fully clarify how this relates to roadmaps, the paper now turns to a specific area of the socio-technical literature, that deals with technological expectations.

3.2. Technology futures in innovation policy: governance of and by expectations

A growing literature on the sociology of technological expectations has emphasised that expectations and social visions play an active role in shaping innovative activities and influencing the technological developments that ultimately occur [42–45]. Scholars in this field describe technological expectations as 'performative', meaning that expectations play a role in shaping the way in which technologies develop.

Expectations lead actors within an innovation system to focus their activities, investment and resources on options that are thought most likely to succeed, with the result that these options become increasingly likely to succeed as further resources are focused on them. Furthermore, expectations are important in the process of aligning actors around common goals. Shared expectations help to establish a common agenda, thus strengthening innovation networks. As a result, expectations can – to some extent – be self-fulfilling [43]. When expectations become widely shared, they shape even the actions of those who *do not* share in the widely held beliefs, since such sceptics know that most others in the innovation system will act on the basis of these shared expectations [46]. Simply put, it is easier to operate within the innovation system when you appear to be in agreement with what everyone else agrees is 'the way things are going'. Shared expectations thus become part of the 'rule set' that constrains and enables particular kinds of activities within the innovation system. Within an evolutionary perspective on technological change, expectations can be understood as important factors in both the generation of variation and in the selection environment [47].

Technological expectations thus help to promote several core functions of an emerging technological innovation system outlined earlier: the mobilization of resources, the development of legitimacy, networking, and establishing clear guidance of the search[1] [27,28,48]. Expectations are also critical in the establishment of niches, or 'protected spaces', in which new technologies can develop [38,49].

The fact that expectations help to shape the direction of innovative activity means that technology futures – scenarios and visions of the future – become a contested space in which various actors compete to establish dominance of expectations that match their interests [11,42]. Thus hydrogen enthusiasts envisage, anticipate and promote a hydrogen future; while many deep green environmentalists predict and describe futures in which social and cultural changes, rather than new technologies, reduce the pressures humankind exerts on our natural environment. This offers an opportunity for governments to attempt to engineer the 'expectations landscape', and hence influence the direction of socio-technical development. Konrad [50] has succinctly summed up this approach by speaking of 'governance of and by expectations'.

Several strands of research have built on the idea that futures can be performative, and have articulated approaches to the use of expectations and futures in the governance of transitions (e.g. [51–53]). Vergragt and others [53–55] have focused on the process of vision articulation and participatory backcasting as a means to foster learning about what is possible in terms of systems innovation, and to build the emerging innovation networks through alignment around a common vision. Their work focuses on the importance of activities within radical niches, arguing that environmental imperatives such as climate change require transitions to systems with radically improved sustainability performance, and that following business-as-usual assumptions and trajectories is insufficient. Participatory backcasting processes are advocated as providing people with a space to rethink cultural practices, and (ideally) to experiment with these in the context of 'bounded socio-technical experiments' [56].

Sondeijker et al. [51] have also focused on the role of visions and futures in transition management, advocating the use of 'transition scenarios'. These are seen as serving many of the same functions as technology roadmaps. "Scenarios provide long-term images of sustainable futures on a strategical level. In this sense, they serve as a framework for short-term actions at an operational level. They ensure the enrolment of actors into coalitions for change and strategic conversation within and between these coalitions. This is supposed to result in alignment and mobilization of collective action necessary to initiate and maintain sustainable system innovations." [51] pp. 20.

There has been little cross-over between 'transition scenarios' theory and those working with technology roadmaps, but the similarities are clear. Indeed, as de Laat has noted, the practice of technology roadmapping has in many ways adopted – perhaps unconsciously – some of the messages from socio-technical theory [57]. In particular, the idea that technical expectations and

[1] Following Hekkert et al. [28], "guidance of the search refers to those activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users".

visions have a performative role, and that they therefore can be 'deployed' as a strategic action in their own right, is clearly embodied in the practice of roadmapping.

Roadmaps, alongside transition scenarios and participatory backcasting, can thus be seen as 'purposefully performative' futures exercises, in which the explicit aim of the process is not just to inform decision making, but to actively shape the behaviour of actors in the innovation system through the development and deployment of a view of the future. This is in contrast to many other foresight approaches, such as exploratory scenarios or Delphi surveys, and suggests that a different set of issues are relevant for evaluating roadmapping processes.

3.3. The roadmapper's dilemma: between opening up and closing down

The use of futures as tools with which to shape transition paths is not without its critics. In particular, the role of a consensus guiding vision in transitions has been questioned on both normative and practical grounds [58]. These critiques are of direct relevance to the use of roadmapping in informing and enacting transitions policy.

At the heart of these critiques lie questions about the extent to which it is desirable and useful to attempt to articulate and champion a *single* coherent view of the future, which 'closes down' the relevant set of perspectives and discourses, as opposed to processes that focus on 'opening up' the articulation of alternative possible futures to encompass a pluralist perspective and more diverse pathways [59].

Of particular concern are issues of politics, power and democratic accountability: if expectations can be deployed as tools with which to shape the direction of socio-technical change, the question of who is involved in informing the development of prospective transition paths becomes central. Shove and Walker have noted that "…[D]espite extensive debate and rhetoric about the construction and democratic choice of visions and images of the future, the depth of the politics involved is frequently underplayed." [60].p. 766. And while several authors writing on roadmaps have argued for the establishment of consensus pathways, it is important to recognise that achieving consensus often entails the exclusion of minority perspectives [61].

Researchers developing transition scenarios and participatory backcasting have acknowledged these difficulties. Indeed, some authors have suggested that the unique value of constructing normative technological visions and roadmaps is neither that they provide a clear set of 'signposts', nor their role in aligning actors and expectations – though these are both acknowledged to be important – but rather that they provide a space for debate and deliberation about technological options and the preferences, values and perspectives of different social groups [21,62,63]. In this view, the articulation of visions and pathways is part of what Stirling calls 'precautionary foresight' [64]—it is a means to open up appraisal of options to wider views, perspectives and framings, rather than a means to develop a consensus plan.

Second, and quite separately from concerns about accountability, the articulation of a single and exclusive transition path appears to ignore the inescapable truth that the future is neither wholly predictable nor wholly malleable. While shared expectations clearly play a role in determining the path of socio-technical development, it is obviously not possible to simply talk ourselves into a sustainable future [65]. In the face of such fundamental uncertainty, attempts to choose and pursue a single transition path are unlikely to be fruitful. Again, researchers involved in participatory backcasting and transition scenarios emphasise the multiple and contingent routes towards a 'guiding visions'. In doing so, they attempt to develop transition pathways that are more robust in the face of uncertainties, and that enable the inclusion of diverse and plural perspectives. Yet experience suggests that actors in the innovation system are unwilling to subscribe to overly diverse, pluralist and contested pathways. The language of inclusivity, diversity and 'opening up' does not breed the kind of confidence and shared sense of purpose on specific investments, projects and technologies that are required for aligning the innovation network.

Roadmaps must articulate a shared view of where things are going – a coherent and reasonably concrete shared direction of search – if they are to provide a basis for action. The roadmapper is thus trapped between two possibilities. On the one hand, a confident, prescriptive roadmap developed on the basis of a consensus of a subset of relevant (and powerful) actors will have most influence. Yet on the other hand, this is likely to reflect incumbent interests—who are often precisely those interests tied up with a less-sustainable socio-technical system and, by focusing on a narrow view of what can and will be done, it can downplay uncertainties and alternative pathways.

The following section develops a set of criteria to address how roadmapping for system innovations can balance these objectives.

4. Criteria for evaluating roadmaps for systems innovation

In this section, I draw on the preceding theoretical discussion to develop a framework through which 'transition roadmaps' may be developed and evaluated. The framework articulates the key attributes that must be addressed if a roadmap is to provide a useful component of transition policy. It is based on a process evaluation, in which the process used to develop the roadmap is assessed, as opposed to an outcome evaluation, since the latter would be impractical given the severe difficulties of attribution in a context as complex as an innovation system [66]. The framework is derived from the preceding theoretical discussion. In particular, the framework aims to assess the extent to which roadmaps are successful at balancing the need to 'close down' the direction to a single, prescriptive view, while remaining responsive and sensitive to the normative and practical critiques set out above.

Given the special character of roadmaps as 'purposefully performative' futures, the evaluation framework differs somewhat from others found in the foresight evaluation literature (e.g. [66]). Despite these differences, there are also clear parallels with the foresight evaluation framework developed by Georghiou and Keenan [66], for example in assessing the quality and type of analysis underpinning the exercise, and in gauging the appropriateness of the roadmapping process.

4.1. Credibility: is the future pathway plausible?

Roadmaps must articulate a view of the future that is credible and persuasive. Without being seen as a plausible view of the future, roadmaps lose their power to direct and shape the behaviour of actors involved in the innovation system.

This has a number of implications for how roadmapping is carried out:

- First, it demands that any analysis on which the roadmap is constructed is sound, and based on reasonable assumptions and methods.
- Second, it requires that the relevant expertise has taken part in shaping the analysis and the roadmap. In the context of a system innovation, such as hydrogen, this implies that a broad range of expertise must be involved, suggesting some form of participatory or consultative exercise with a broad range of expert stakeholders.
- Third, credibility demands that the actors with greatest ability to influence achievement of the envisaged futures are involved, and are – at least to some extent – committed to that future. The roadmapping process must secure the commitment of key actors to the process, and must communicate that these key actors believe in the roadmap.
- Finally, credibility requires that the roadmap engages adequately with the social, political, market and cultural aspects of the envisaged transition, as well as the 'purely' technological elements. A roadmap that fails to set out a plausible view of market and social contexts, but envisages profound technological systems change, will be less credible than one that embeds a vision of technological change within a broader context of anticipated market and socio-political evolution.

4.2. Desirability: is the future pathway defensible as a good choice for society?

Those developing roadmaps within a public policy context have a responsibility to articulate a future pathway that is desirable from a societal perspective. This begs the question of who gets to decide what kind of future is in the interests of society, and on what basis such decisions are made.

Clearly, the desirability of the envisaged future can be based on goals and directions established through existing democratic institutions. For example, analysis might show that hydrogen technologies can enable emissions reductions to meet legislated carbon targets. However, guidance from legislatures typically provides insufficient clarity in making choices about which technological pathways to pursue.

Those developing transition roadmaps must make choices about how to determine a desirable direction for socio-technical development. The roadmapping literature emphasises the desirability of establishing consensus amongst the stakeholders involved [3,67]. Yet in a pluralist democratic society, it is not always straightforward – or even necessarily possible – to establish a clear consensus view of the desirability of a given future pathway [68,69]. To overcome this challenge, the framework in this paper adopts a deliberative democratic perspective, which demands that public policy decisions are accountable, in the very literal sense that a clear 'account' is given of why a decision was made in that way [68]. Rather than demand that roadmaps set out a future for which there is a broad social consensus, evaluation of the roadmap should instead focus on the degree to which roadmaps can justify the choices made in deliberative terms. In other words, roadmaps should be explicit and transparent in their aims, the process used, and who took part.

Finally roadmaps that are developed through processes that are broadly inclusive and participatory will have a greater claim to setting out a legitimately desirable future pathway. Work on network governance (an appropriate theoretical frame for innovation system governance) has emphasised the importance of inclusivity [70]; and, as discussed, many theorists of technology argue persuasively that broad participation is important in both appraising and committing to particular technological futures [71]. This is not to say that participation is a clear route to democratic legitimacy, but rather that roadmapping processes that exclude opportunities for participation are less able to claim legitimacy.

4.3. Utility: does the roadmap help advance the innovation system?

The third criterion relates to utility: does the roadmap and roadmapping process facilitate the further development of the innovation system? In other words, does it help the innovation system to perform core functions of innovation systems, as described by Bergek et al. [27]?

Where roadmaps meet criteria 1 (credibility) and 2 (desirability), they automatically help foster legitimacy for the technology in question, which is a core function of a successful innovation system. Beyond this, to be useful the roadmap must provide a coherent direction of search for scientists, engineers, entrepreneurs and other innovation system actors. A shared research agenda enables alignment of enactors and selectors, and a roadmap is one of the ways in which this function can be facilitated. Any roadmap provides the broad direction of search, in the sense that it articulates a place for the technology in the world. Beyond this, a roadmap should identify specific research needs and priorities, highlighting what Hughes referred to as 'reverse salients' [10]. Depending on the degree of maturity of the innovation system, this may involve setting detailed, technically-defined 'targets'. Alternatively, it may only highlight areas that are of particular concern.

Roadmaps must navigate a careful balance between setting out a confident view of a plausible and desirable future, and over-promising and 'hype', which can damage the prospects of the innovation system [72].

Finally, the roadmapping process must be appropriate for the stage of the innovation system [66]. For innovation systems in an early, formative stage, for example, setting very long-term technical targets may not be helpful if the capacity to work towards meeting them does not exist. In such a situation, a roadmap that sets out a broad framing vision of the path forward is likely to be more useful.

4.4. Adaptability: is the roadmap process consistent with reflexive, adaptive management?

The literature on transition management emphasises the need for continual adjustment and re-evaluation of policies and programmes, and the literature on roadmaps in industry has emphasised that roadmaps are more effective where they are developed as an ongoing process rather than a one-off document (e.g. [5]). As Propp and Rip [73] have argued "Roadmaps need to be maintained and updated to become effective. Where an actor to fulfil that function exists… roadmaps become a powerful tool for creating alignment around technological and product options and to help accelerating their development" (p. 11). This argues for roadmaps to be developed and maintained within an institutional context – such as a partnership between government and industry groups – that is able to learn, and to produce updates to the roadmap as time goes by.

Ideally, the actor(s) responsible for producing and maintaining the roadmap will do so in a reflexive manner, one that emphasises learning and evaluation, and is open to reflection on the role and value of the roadmapping process and its framing. In the context of transition management, Shove and Walker [60] highlight that the question of 'what is to be transitioned' is frequently not a matter for debate. In the same way, roadmapping lacks obvious mechanisms through which to adequately justify how transition questions are framed and determined. As with the substance of the roadmap itself, the institutional structures through which roadmaps are identified and framed should be transparent, and able to reflect critically on the framing of the exercise overall. In effect, this requires that roadmapping processes sponsored by government should be conducted within a broader context of technology foresight and strategy governance processes.

4.5. Summary: evaluation criteria for transition roadmaps

Table 1 summarises the criteria, and highlights the key questions addressed by each criterion.

5. The case of hydrogen

Hydrogen, like electricity, is an energy carrier that can be produced and used in a variety of different ways. Like electricity, the environmental attributes of hydrogen depend largely on how it is produced and used, since it is not a significant pollutant in itself [74]. While there has been a decline in excitement in policy circles about hydrogen since around 2005 [72,75], it remains an important option for deep decarbonisation of the transport sector and for diversification of energy sources for transport, and potentially as a widespread carrier of energy for heat and power demands.

Hydrogen has been a vibrant arena for the development of roadmaps [67,76]. National and regional governments, US States (e.g. Ohio, California, Connecticut, New York, Florida, Indiana, Minnesota and others), and a number of cities across the globe have undertaken roadmapping activities concerning hydrogen, alongside numerous firms and industry associations.

A sample of hydrogen roadmaps produced in the last 10 years was reviewed, with a focus on those produced as part of policy processes by national governments (or supra-national, in the case of the EU). Roadmaps were identified by searching online databases and through stakeholder interviews. The review focused on those addressing hydrogen directly, aiming to identify those that have been used as part of a broader policy process that aims to address the transition to a hydrogen energy system. However, hydrogen technologies are developed and managed within the context of a broader portfolio of innovative energy technologies, and so the review identified the following types of relevant roadmaps:

- Hydrogen energy and fuel cell roadmaps
- Low carbon vehicle roadmaps (that include hydrogen)
- Low-carbon energy technology roadmaps (that include hydrogen)

Table 1
Summary table of criteria for transition roadmap evaluation.

Criteria	Key questions
Credibility	Is the roadmap based on sound analysis?
	Does the roadmap draw on the right breadth of expertise?
	Has the roadmap secured the participation and commitment of key actors in the innovation system?
	Does the roadmap adequately address the political, social and economic aspects of the transition?
Desirability	Does the transition meet social goals established through democratic institutions?
	Does the roadmap give a clear account of the justification for the proposed pathway, with transparency in aims, process and who took part?
	Is the roadmap process inclusive and participatory?
Utility	Does the roadmap effectively articulate a path forwards that can enable alignment around common goals?
	Is the roadmapping approach appropriate for the stage of innovation system maturity?
Adaptability	Does the roadmapping process involve periodic reviews, updates and learning?
	Is the roadmapping process embedded in a broader institutional structure that enables reflexivity and learning?

Table 2
Roadmaps included in the review.

Roadmapping initiative/document(s)	Abbreviation	Country/region and year	Core sponsors; reference
Hydrogen technology roadmap	AUS	Australia 2008	Government of Australia [77]
Canadian fuel cell commercialization roadmap; Canadian fuel cell commercialization roadmap update	CAN03, CAN08	Canada 2003, 2008	Government of Canada [78], Hydrogen and Fuel Cells Canada [79]
Hydrogen energy vision and technology roadmap report for China	CN	China 2004	Ministry of Science and Technology, China [80]
HyWays: the European hydrogen roadmap	HyWays	EU 2008	European Commission [81]
Hydrogen energy and fuel cells: a vision of our future	EUHLG	EU 2003	European Commission High Level Group on Hydrogen and Fuel Cells [82]
European Hydrogen and Fuel Cell Technology Platform: deployment strategy, strategic research agenda and implementation plan	EUHFTP	EU 2005, 2006 and 2007	European Commission Hydrogen and Fuel Cell Technology Platform [83–85]
The GermanHy roadmap	DE	Germany 2008	German federal government and the German National Organisation for Hydrogen and Fuel Cell Technology [86]
The Icelandic hydrogen energy roadmap	IC	Iceland 2008	Icelandic Ministry of Industry and Commerce [87]
National hydrogen energy roadmap: pathway for transition to hydrogen energy in India	IN	India 2007	Indian Ministry for New and Renewable Energy [88]
Strategic technology roadmap (energy sector)	JPSTR	Japan 2005	Japanese Ministry of Economy, Trade and Industry [89]
Cool earth innovative energy technology program: technology development roadmap	JPCE	Japan 2008	Japanese Ministry of Economy, Trade and Industry [90]
Fuel cell vision for the UK; and UK fuel cell development and deployment roadmap	UKFC	UK 2003, 2005	Fuel cells UK and Department for Trade and Industry [91,92]
Roadmap for hydrogen energy in the UK	UKH2	UK 2009	Technology Strategy Board, Department for Energy and Climate Change, UK Hydrogen Association [93]
A national vision of America's transition to a hydrogen economy — to 2030 and beyond; national hydrogen energy roadmap	USH2	US 2002	US Department of Energy [94,95]
Fuel cell technologies roadmap; hydrogen production roadmap; hydrogen delivery roadmap; hydrogen manufacturing R&D roadmap	USFCAR	US 2005, 2009, 2007, 2005	US FreedomCAR and Fuel Partnership [96–99]

The review included roadmaps from: the US, Australia, India, the UK, Japan, China, the EU, Iceland, Germany and Canada. In some countries/jurisdictions, more than one roadmap was examined. In total, 15 roadmapping initiatives were included in the review (see Table 2). Abbreviations, listed in Table 2, are used to ease the referencing and readability of the paper.

The review was conducted using a standard template to extract a consistent set of information from each document. While the review focused on the documents themselves, the review also examined further documentary evidence to inform the institutional context behind the roadmaps (i.e. how were they produced, how are they being used).

6. Evaluation of hydrogen roadmaps: a socio-technical perspective

Governments have used roadmaps to inform and promote the development of hydrogen energy in a variety of ways. The style and approach include roadmaps built on intensive, multi-year and analytically rich processes (e.g. HyWays), short overview roadmaps built on the basis of a single workshop (UKH2), and ongoing roadmapping processes that are embedded within broader energy technology strategy (JPCE). This section applies the framework developed in Section 3 to the literature, to examine how governments are using roadmaps for a transition to hydrogen energy.

6.1. Credibility

6.1.1. Are roadmaps informed by good quality analysis and broad expert participation?

The quality and depth of technical analysis underpinning roadmaps varies considerably. In many cases (e.g. USH2, UKFC, EUHLG, IC, CN03, IN), analysis focuses on mapping the actors and institutions involved in hydrogen and fuel cells, and market opportunity assessment. Rather fewer roadmaps explicitly include technological forecasting of future cost/performance or technology needs assessment (e.g. HyWays, AUS). Analytic modes include both forecasting (identification, examination and projection of market and technology trends) and backcasting (identification of steps that need to be taken in order to reach an established goal).

Some of the roadmaps are informed by detailed modelling exercises, sometimes involving multiple modelling approaches. The German, HyWays, and Australian roadmaps included detailed modelling studies of hydrogen costs and competitiveness. Other roadmaps were informed by relatively simplistic analysis, including simple extrapolation of historical sales figures many years into the future (e.g. CAN03). Across the studies, analysis of technological goals and needs appears to be more robust than analysis of future markets and opportunities. This is perhaps not surprising: the former is concerned with providing clear, informed direction to innovators; while the latter is subject to the inherent tension within roadmaps: providing confidence in the future of the technology, without contributing to potentially damaging 'hype' cycles. In retrospect, the market analysis that contributed to some of the earlier roadmaps reviewed (such as CAN03) can be seen as has having contributed to early hype about hydrogen. All the roadmaps involved some form of participatory or consultative process through which to engage expert stakeholders.

6.1.2. Participation and commitment of key stakeholders

Roadmap credibility depends on the participation and commitment of key stakeholders whose actions are critical in the further development of the system, such as major firms involved in automotive and fuel supply markets. All the roadmaps reviewed attempted to secure the participation or commitment of stakeholders through consultations or participatory processes. In several cases, participatory workshops were the main input into roadmap development (UKH2, CN, USH2).

Governments are central players in the development of a hydrogen energy system, since policy support is necessary to overcome the barriers associated with an infrastructure transition [76]. While all the roadmaps were either produced or sponsored by governments, there are obvious differences among roadmaps in the degree of commitment from government and from other major stakeholders. Some are endorsed at the highest levels of government, and are associated with the participation and engagement of major industries (e.g. USH2, USFCAR, JPSTR, JPCE, EUHLG, IN). Others are published or sponsored by governments, but without obvious high-level political endorsement, such as a preface by a senior minister (e.g. UKH2, UKFC, CN, HyWays). Several of the more technically-detailed roadmapping exercises were sponsored by government, and produced through formal collaborative partnerships made up of industry, government and research organisations, with working groups addressing particular issues (e.g. EUHFTP, USFCAR). These partnerships involve a degree of commitment from all participants to the process, and may be seen as producing more credible views of future pathways.

6.1.3. Adequate engagement with social, political and economic aspects

Most of the roadmaps engage to some extent with broader social, political and economic aspects of a transition, in the form of addressing future market needs, energy and transport demands, and the policy drivers that are informing the broader social context for hydrogen energy. In some cases, future consumer requirements (such as acceptable vehicle range) or market conditions (such as carbon constraints) are set out in specific details.

In all the roadmaps, the future is much like the present in terms of consumer behaviour, cultural practices and transportation patterns. This is in strong contrast to many hydrogen futures developed by NGOs, academics and visionaries, many of which describe futures that associate the establishment of a hydrogen energy system with widespread shifts in social values or structures. Discursive themes around 'ecotopia' or radical decentralization and democratization, present in many hydrogen futures [100,101], are entirely absent from the roadmaps. As a body of visions of the future, the roadmaps are strikingly conservative in their representation of how future people and societies will meet their needs. This can be viewed as a failure to engage with broader uncertainties around socio-technical change, or simply as a tacit set of assumptions about the durability of social structures and practices.

However, many of the roadmaps do depart from current social norms in their depiction of the governance mechanisms that might accompany the transition to a hydrogen energy system. Several of the roadmaps envisage a future in which a transition is effected through corporatist collaborative governance models involving partnerships of major industries (principally automotive and oil companies) with governments. This view envisages government–industry partnerships making major investment decisions in infrastructure and manufacturing capacity in a co-ordinated way, enabling a hydrogen system to overcome the enormous challenge of establishing an entirely new vehicle refuelling infrastructure solely because of the benefits of the new fuel to society. In other words, while the roadmaps reviewed tend to be rather conservative in their views of social practices and consumer behaviour, they envisage new governance models for purposive socio-technical transitions.

6.2. Desirability

Very few of the roadmaps incorporate a detailed analytic case for pursuing a hydrogen future (exceptions are HyWays and DE). Rather, most build an argument based on the key public policy drivers (climate change, energy security, air pollution, and international competitiveness). Where there is detailed analysis of hydrogen energy systems, these are not compared with alternatives (such as transport systems based on battery electric vehicles) on a like-for-like basis. The analytic work underpinning roadmaps, while often sophisticated, can thus be seen as providing justification, rather than supporting decision-making and deliberation.

All of the roadmaps are based on some form of participatory or consultative process, involving a range of stakeholders. Roadmaps differ in the degree of transparency about who was involved, with many not making clear who participants were. None of the roadmaps identified how participants were selected. Similarly, the roadmaps do not make clear how or whether consensus was reached. Few of the roadmapping processes appear to have directly included broader voices from consumer or citizen perspectives, such as elected officials, participants from civil society groups or NGOs, or simply interested or concerned citizens. In other words, the participatory processes through which roadmaps were developed were tightly framed and constrained in their modes of participation and representation, and cannot be seen as providing a strong basis for social legitimacy to the hydrogen futures envisaged.

6.3. Utility

All the roadmaps provide a broad, high-level vision. They frame hydrogen energy as a major area for future development, and as a priority for R&D and investment activities. In this sense, roadmaps are all useful in endorsing the legitimacy of hydrogen technologies as a focus for innovative activity.

Some roadmaps are limited to this broad, generic view. Examples of these roadmaps include CAN03, USH2, CN, IN, UKFC, UKH2, and AUS. These roadmaps project a sense of vision and the pathway of development, but with limited technical detail or specific targets. These 'framing roadmaps' are typically produced as an initial attempt to clarify the state of the emerging innovation system and its prospects. They deploy a coherent 'technology story', deploying generic expectations (in the sense used by van Lente and Bakker [44]) about the promise of the field in general, rather than expectations about specific technological details. Their purpose can be understood as primarily political, doing the work of establishing and legitimating a frame through which to understand and relate to hydrogen technologies. Many of these roadmaps lack substantial technical detail, and while they typically provide an overview of the relevant technologies, they provide only limited guidance to innovators in terms of focusing on research challenges. These roadmaps may describe the technologies in detail, but they are typically empty of the forward-looking technology analysis that is usually seen as a defining characteristic of technology roadmapping activities. They are most appropriate for the formative phases of an innovation system.

Other roadmaps combine this generic vision with specific technical detail. In these technically-detailed roadmaps, governments work with academia and industry to establish R&D targets and detailed technological milestones against which progress can be assessed. Examples of this mode of roadmapping include the USFCAR, HyWays, EUHFTP, JPSTR, and JPCE. Some of the roadmaps establish milestones and decision-points. For example, the US roadmapping processes highlight a decision point in 2015 on full-scale commercialization of fuel cell vehicles.

Both of these modes ('framing' and 'technically-detailed') can be understood as providing a coherent direction of search, but for different stages of innovation system maturity. For an emerging innovation system, in which alignment of actors is poor and shared expectations are weak, it is necessary to first provide an overarching framing roadmap through which to facilitate the coalescing of the innovation system. Only once this broader framework has become accepted is it possible to provide more specific direction.

6.4. Adaptability

Most of the roadmaps reviewed appear to be one-off exercises, rather than ongoing management processes. This is particularly true for the 'framing' roadmaps, which tend to set out a strategic view rather than a detailed structure for monitoring progress (e.g. CN, IN, AUS, UKH2).

A minority of the hydrogen roadmapping processes reviewed have been subject to updates and reviews. The development of sequential US roadmaps has been taken forward by the FreedomCAR and Fuel Partnership, a joint initiative of government, automotive firms and energy companies. In Japan, the Ministry for Economy, Trade and Industry (METI) has developed hydrogen roadmaps as part of its broader process of Strategic Technology Roadmapping, which includes reviews of roadmaps every 2 to 3 years [102]. The Canadian hydrogen roadmap has been updated, and radically revised, by the industry body Hydrogen and Fuel Cells Canada. The roadmaps developed by the European Commission have not explicitly been reviewed and updated, but they have formed a sequence of related roadmapping initiatives, managed through an evolving institutional structure (first the High Level Group on hydrogen and fuel cells, followed by the Hydrogen and Fuel Cell Technology Platform, and now the Joint Undertaking on Hydrogen and Fuel Cells).

7. Conclusions

This paper has described the way in which governments have increasingly been using the practices of technology roadmapping to inform and shape long-term systems innovations, or technological transitions. In reviewing hydrogen roadmaps, and evaluating them from a socio-technical perspective, the following conclusions can be drawn:

- The theoretic literature on transition management and the role of expectations suggests that roadmaps can be a valuable complement to transition management policy. Their use in such contexts reflects a rise in the use of 'systemic instruments' [103] in innovation for sustainability, and this is to be welcomed. However, none of the roadmaps reviewed fully met all the criteria, and there appears to be considerable scope for improvement in roadmapping practice for long-term transitions.
- The roadmaps reviewed vary in the quality of analysis on which they are based. Some draw on strong analysis, with well-established methods and transparent assumptions. However, there are also many roadmaps that appear to be based on weak analysis or that lack sufficient transparency to judge the robustness of the conclusions on which the roadmaps are based. This is potentially damaging: poor quality and opaque analysis results in unrealistic expectations, and can exacerbate hype-cycles, undermining the development of the innovation system.
- All of the roadmaps involved some form of consultative or participatory process involving key stakeholders. However, some of the roadmapping initiatives appear to have been conducted without ensuring participation and buy-in from key players in the innovation system, which limits the credibility – and therefore the utility – of the resulting futures. Those initiating roadmapping processes should ensure that they have sufficient resources and credibility to attract key participants to commit to the process.
- Few of the roadmaps set out an adequately argued case for the desirability of hydrogen futures. Most roadmaps clearly identify the drivers and motivations for developing a hydrogen energy system (climate change, energy security, air pollution and the development of new industries), but few adequately demonstrate that hydrogen is a likely or preferable means to achieving those ends.

- Roadmapping processes are often insufficiently transparent and are often closed to broader participation. Technology roadmaps, when used to address systems innovations, are attempts to engineer a landscape of expectations that is conducive to the development of a new socio-technical system. They can and should be a site of democratic engagement and debate about the direction of socio-technical change. Broader consultation and public input is common practice in many other fields of policy development and should be more common in roadmapping.
- Many roadmaps are conducted as one-off exercises. This is unfortunate, as roadmapping should enable a structure for learning about a transition as it unfolds. Those developing roadmaps should, where possible, institutionalize the updating and ongoing evaluation of roadmaps. In other words, roadmappers should allow roadmapping processes to operate in a reflexive, learning mode, through an established institutional arrangement.

The work has highlighted the potential of transition roadmaps as one type of 'systemic instrument' in the governance of transitions. Two priorities for further research can be identified from this initial study.

1. The relationship of transition roadmaps to other foresight approaches. This paper has suggested a distinction between roadmaps, as 'purposefully performative' futures, and most other kinds of foresight activity. However, many of the issues raised in the paper also apply to other foresight approaches when considered in the broader context of transition management. In particular, there is a need for clearer insight into the way in which different foresight activities can be used to enable either "opening up" or "closing down" of appraisal and commitments within the innovation system.
2. The institutional structure and design of transition roadmapping processes requires further development. This paper has highlighted ways in which the tools of technology roadmapping can be used to inform and shape socio-technical transitions, and it has provided a broad framework for the application of this approach. Further study on the dynamics of roadmapping processes, and the impact of roadmaps on innovation system development, would be valuable in shaping recommendations about the detailed design and structure of roadmapping processes as part of innovation and transition management policy.

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