Journal of Cleaner Production 206 (2019) 878–892

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

The theoretical foundations of sociotechnical systems change for sustainability: A systematic literature review

Paulo Savaget [a, *], Martin Geissdoerfer [a], Ali Kharrazi [b, c], Steve Evans [a]

[a] Institute for Manufacturing, Department of Engineering, University of Cambridge, Cambridge, CB3 0FS, United Kingdom
[b] Advanced Systems Analysis Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, A-2361, Austria
[c] Graduate School of Public Policy, The University of Tokyo, 113-8654 Tokyo, Japan

ARTICLE INFO

Article history:
Received 22 November 2017
Received in revised form
19 September 2018
Accepted 24 September 2018
Available online 25 September 2018

Keywords:
Sociotechnical systems
Sustainability
Innovation
System change
Systematic literature review

ABSTRACT

This paper provides a critical literature overview of the foundations of the concepts of sustainability and sociotechnical systems change. This review covers the analysis of 182 scientific articles through a combination of bibliometric analysis, snowballing, content analysis and problematization. Our results identify and discuss 14 unique ontological and normative foundations shaping how we understand sociotechnical system change for sustainability. These influence both what system change is perceived as desirable and as attainable; as well as how to navigate between all the coexisting pathways, trade-offs, and complexities of the three dimensions of sustainability. By identifying the theoretical foundations, we illustrate the most up-to-date theoretical developments and concomitantly pinpoint a few opportunities for future contributions that improve, refute or complement them, hence shedding light on various research questions to develop the literature further.

Contents

* Corresponding author.
E-mail address: ps687@cam.ac.uk (P. Savaget).

https://doi.org/10.1016/j.jclepro.2018.09.208

1. Introduction

Sustainability can be framed as the integration of social inclusiveness, environmental protection and economic resilience for the benefit of current and future generations (Brundtland, 1987; Elkington, 1999). There is growing concern to transition towards more sustainable directions. Pressing issues include, for example, biodiversity loss; water, air, and soil pollution; climate change; unemployment and poor working conditions; poverty trap and social vulnerability; widening inequalities; and financial volatility (e.g. Seiffert and Loch, 2005; Markard et al., 2012; Sachs, 2015; Jackson, 2009).

Standalone, incremental improvements are not sufficient to address current, let alone future sustainability challenges (Evans et al., 2009). These challenges will require deep changes of socio-technical systems. This term refers to co-evolving social and technical aspects, which are analysed according to arbitrarily defined boundaries – such as organizations, sectors or nations (Geels, 2004; Savaget and Acero, 2017). Theories on innovation systems; sustainable innovations; system thinking and design; and sustainability transitions, among others, have attempted to describe potential changes capable of shifting development towards more sustainable directions.

System thinking and design contributed greatly to a holistic understanding of system change, including ways to make its parts work together, while dealing with multiple and often unpredictable sources of instability, discontinuity, and resistance to change (e.g. Senge, 1990; Meadows, 2002). Studies on innovation systems, more specifically, influenced the understanding of co-evolutionary dynamics of sociotechnical change, including the connections between knowledge and technologies, institutions, actors and networks (e.g. Freeman, 1991; Malerba, 2002).

Along these lines, several studies have been dedicated to studying how to steer sociotechnical system change to address pressing sustainability challenges. Sustainable innovations literature, for example, describes the generation and diffusion of innovative products, services, processes and business models contributing to improved social and environmental performance (e.g. Seyfang and Smith, 2007; Esty and Winston, 2009). Sustainability transitions theory, alternatively, focuses on advancing the understanding of highly institutionalised processes that constrain sustainable innovations in their attempts of leapfrogging the prevailing unsustainable alternatives – thereby constraining path-breaking and wide-scale changes (e.g. Geels, 2002; Smith et al., 2005).

Despite their different approaches, all these contributions emphasise that unsustainable characteristics of prevailing socio-technical systems are not easily changed, as they are part of mutually-reinforcing dynamics, encompassing, for example, technologies, policies and social behaviours. The literature has responded to these challenges by investigating the intensities and causalities of these developments; hence, contributing towards a better understanding of the multiple and co-existing possibilities to purposefully drive sustainable changes.

It seems clear that knowledge on how to analyse and describe sociotechnical system change has gained academic prominence as means of shifting progress towards meeting the most pressing sustainability challenges of our time (Leach et al., 2007; Clark and Crutzen, 2005; Kates et al., 2005). However, there has been no systematic effort to reveal the dominant ontological and normative perspectives grounding theoretical development in this field, hereby called as 'theoretical foundations'.

Ontologies refer to the nature of reality (Grant and Giddings, 2002), to what we think 'things are' (Savaget and Acero, 2017). That encompasses questions, for example, of what we believe a sociotechnical system is, how it changes and what changes are attainable. Normativities, on the other hand, consist of views of what 'we think things should be', instead of 'what they are'. That includes, for instance, questions on what is a desirable socio-technical system, how it can be best steered towards reaching more desirable outcomes, what should change, and what should be prioritised (Stirling, 2009).

Theoretical foundations are, thus, a combination of ontologies and normativities: evaluative frameworks for analysing reality and taking decisions. They are highly influenced by hegemonic institutional, political and cultural commitments, and exposing them can lead to a reflection on novel research questions to contribute to theory and practice.

Aiming at filling this research gap, this article focuses on the following research question: *What are the theoretical foundations of sociotechnical systems change for sustainability?* This question was addressed through a systematic literature review. Besides yielding a better understanding of the state-of-the-art of literature, this process opens up scope for reflecting upon its shortcomings and for questioning novel research avenues contributing to furthering theoretical development.

The remainder of this paper is structured as follows: Section 2 explains our methodological approach; Section 3 scrutinizes our findings; Section 4 discusses the results; and Section 5 concludes this article, by discussing opportunities for future research.

2. Methods

This literature review aims at investigating the theoretical foundations of sociotechnical systems change for sustainability. It does so by revealing the main foundations, which influence boundaries and prospects for future theoretical development. As illustrated in Fig. 1, this literature review consists of a combination of structured and semi-structured stages, including four distinct process steps.

We started with a bibliometric analysis, guiding the initial sampling of papers. This initial sample was subsequently complemented by semi-structured snowballing to expand the literature and compose the final sample. We thereafter conducted a content analysis to reveal and categorise foundations underlying theoretical developments. Finally, this analysis allowed us to problematize the prevailing theoretical foundations and identify areas for future contribution. These steps are clarified in the following subsections.

2.1. The sampling stage

Systematic reviews are used as key mechanisms to promote diversity of knowledge in a certain domain (Easterby-Smith et al., 2015). If conducted diligently, the process of inclusion or

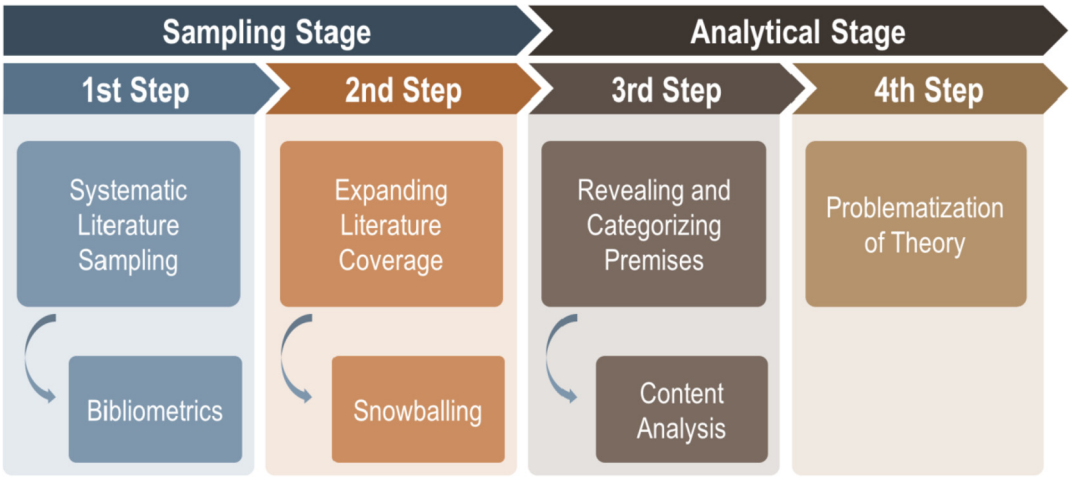

Fig. 1. Methodological steps for literature review.

exclusion of theoretical contributions is not implicitly biased as in conventional approaches, that may underrepresent certain perspectives (Tranfield et al., 2003). We adopted a replicable and transparent process for inclusion or exclusion of references in the review, which consequently provided audit trails to question the employed criteria and the identified conclusions (Pittaway et al., 2004).

The process started by collecting and analysing bibliometric data to inform the initial sampling of papers for the review. Bibliometric analysis scrutinizes published data, measuring text content and bibliographic information such as authorship, affiliation, citations, and keywords (Bellis, 2009). It can be used to describe, evaluate and monitor the state of a field over time. We employed it to identify the most cited journals, scholars, and keywords to choose a sample capable of informing about these prevailing theoretical foundations. As we aimed to obtain a comprehensive historical perspective of the literature, at this stage, we did not filter our data collection by date, geography or discipline.

Data was collected from the Web of Science database in January 2016, following recommendations of Webster and Watson (2002). As literature recognises that incremental and standalone changes in sociotechnical systems will not be sufficient to address sustainability challenges, our first focus was on theories covering wide-scale sociotechnical change. We then searched for the strings "sociotechnical transition" OR "strategic niche management" OR "sustainability transitions". We also checked for an alternative, hyphenated spelling of the word sociotechnical (i.e. socio-technical). The resulting dataset of 565 records was then analysed through statistical and networks approaches with the software Hammer (Knutas et al., 2015).

As illustrated in Fig. 2, the field has grown steeply between the period of 2008 and 2016, reaching more than 6-fold the number of

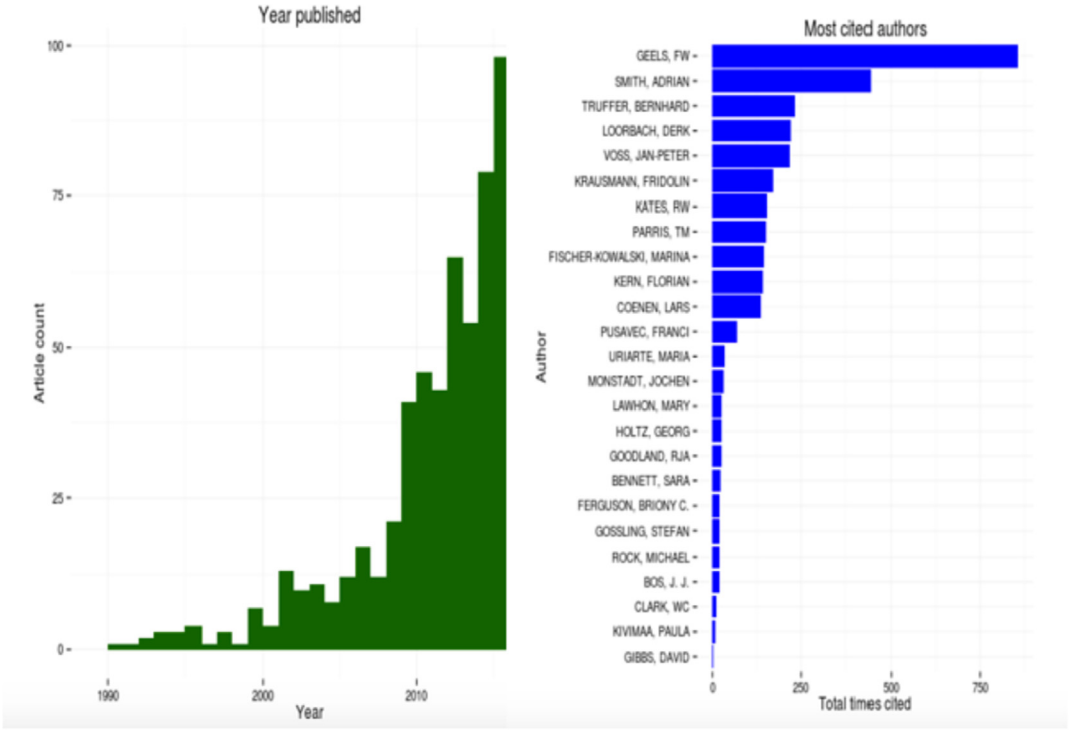

Fig. 2. Bibliometric results – evolution of the field and most cited authors.

publications on our research topic. There is also a great disparity in numbers of citations, suggesting that, despite the growing number of publications, a few authors are much more influential than others.

Based on its analysis, the top ten most cited papers were selected for further review. Since we are interested in revealing ontological and normative foundations of theory, number of citations was a good initial metric for sampling: the more cited, the higher the likelihood of reflecting pervasive perspectives among scholars. In order to supplement the sample with more recent and emerging research, the five most cited papers published between 2014 and 2016 in the most influential journals, based on the results of our bibliometric analysis, were also included into the review. Finally, to better expose future research motivations and expectations, a report discussing the Mission Statement of the Sustainability Transitions Research Network (STRN, 2010), a leading research group in the field, was also included in the review. Table 1 depicts the author name, year, and journal of the initial 16 papers for the literature review.

To gather comprehensive data on theories influencing this research terrain, the snowballing technique was adopted (Wohlin, 2014) to cover an extensive range of additional literature – following the approach of Geissdoerfer et al. (2017). We revealed the cross-fertilisation between concepts, as well as how theories evolved and developed interconnections through time.

The snowballing process is illustrated in Fig. 3, where blue indicates the definition of the initial sample, light brown the beginning of the iterative snowballing process, and dark brown the end of our data collection. We examined the relevance of these papers for inclusion/exclusion by analysing their titles, contents, and abstracts. Relevant papers are defined as the ones capable of contributing with novel insights on similarities, differences or relationship types between the studied concepts. Furthermore, if a new paper was included in the sample, its references were also examined for new inputs – these iterations would continue until no new and significant insight relevant to the research questions was found. This process resulted in a final sample of 182 documents.

Table 1
Initial sample for literature review.

Source	Journal
(Kemp et al., 1998)	Technology Analysis and Strategic Management
(Geels and Schot, 2007)	Research Policy
(Schot and Geels, 2008)	Technology Analysis and Strategic Management
(Smith et al., 2010)	Research Policy
(Kemp, 1994)	Futures
(Geels, 2010)	Research Policy
(Markard et al., 2012)	Research Policy
(Shove and Walker, 2010)	Research Policy
(Kates and Parris, 2003)	PNAS
(Smith and Raven, 2012)	Research Policy
(Sushandoyo and Magnusson, 2014)	Journal of Cleaner Production
(Pincetl et al., 2014)	Landscape and Urban Planning
(Wittmayer and Schäpke, 2014)	Sustain Sci
(Shaw et al., 2014)	Global Environmental Change
(De Haan et al., 2014)	Technological Forecasting and Social Change
(STRN, 2010)	A mission statement and research agenda for the Sustainability Transitions Research Network

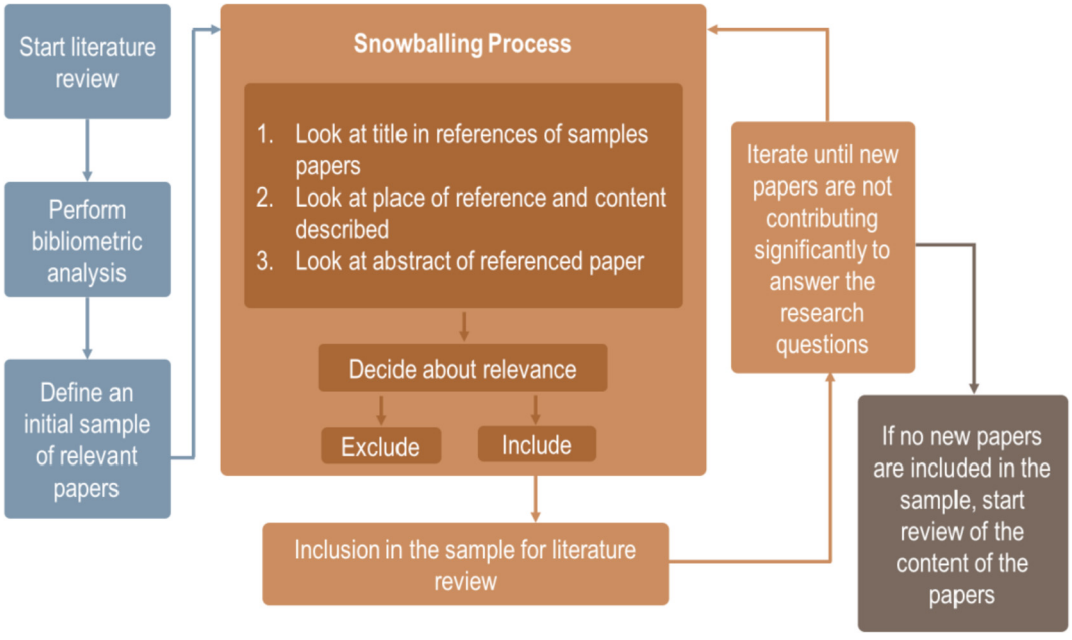

Fig. 3. *Snowballing Process* (Geissdoerfer et al., 2017).

2.2. Analytical stage

Most academic endeavours are focused on extending the coverage of literature, or filling gaps that have been neglected by previous research (Alvesson and Sandberg, 2011) rather than challenging embedded foundations of existing theories. Since this research aims at revealing theoretical foundations, it follows the approach introduced by Whetten (1989) who assumes that the most relevant theoretical features lie on knowledge on *Why, What* and *How*.

What and *How* describe approaches to understand a phenomenon, while *Why* explains the motivations leading to such conceptual developments. Together "they provide the essential ingredients of a simple theory: description and explanation" (Whetten, 1989:491). *When*, *Who* and *Where* are categories covering temporal or contextual factors, responsible for setting the boundaries for theoretical generalisability. In what jurisdiction are these predictions valid? In what timeframe is this phenomenon applicable? What agents are accountable for (or influenced by) this event? These kinds of questions only limit the propositions, set the boundaries for contributions, and expose the pervasiveness of a phenomenon (Whetten, 1989).

In this work, we were focused on the foundations (*Why*, *How* and *Why*) of theories of sociotechnical system change, and not on contextual characteristics (*Where*, *Who* and *When*). We conducted content analysis with the assistance of the software Nvivo. This process allowed us to analyse written communication through thematic interpretation of the 182 articles in our final sample by attentively reading them to code relevant extracts (Weber, 1990). We coded the data with the support of our previously established categories (*What*, *Why*, *How)*. Subcategories then arose throughout the process, allowing us to compile, group and summarize data according to their specificities and draw their interconnections (i.e. the 24 subcategories described in the column "What does it include" of Table 2). As a result, this process provided a condensed description of the most relevant foundations of our field of research.

Our approach has the following limitations. Our data was initially collected from the Web of Science database and was subsequently expanded through snowballing. Therefore, relevant publications not covered by the database are not included in the initial sample. Since snowballing only addresses publications cited by, and therefore published before the publications in our sample, research areas emerging after our initial sample collection were not included. This also applies to publications at the margins of the research field that have not been sufficiently cited. Furthermore, our content analysis was conducted in a structured and systematic fashion but involves some levels of subjectivity in defining relevant extracts through codification.

3. Results

In total, 182 prominent documents on sociotechnical system change for sustainability were collected and analysed. The first output of our content analysis was the categorization of our sample into research areas, whose contents were then contrasted and scrutinised. The six main research areas are Governance of Innovation Systems; Public Understanding of Science, Technology, and Society; Innovation Management; Sustainable Development; System Thinking and Design; Wide-scale Socio-technical change. The content of each category and representing publications in the literature are illustrated in Table 2.

This table pinpoints the most notable themes explored by each research area, as well as their main references. This overview provides a glimpse of the breadth and scope of the literature on sociotechnical system change for sustainability.

Our second output was then to build a narrative, based on our textual coding, that summarises the Why, What and How embedded and widely diffused into literature – as described in the following subsections. We are particularly focused on exposing the main sources of agreement and tension within literature. After presenting them, we could then synthesise the theoretical foundations, which are outlined and discussed in Section 5.

3.1. Why?

The covered literature reveals two main underlying motivations. The first refers to the understanding of sustainability goals. The second consists of understandings of why sociotechnical systems should be addressed to influence such goals.

3.1.1. Why sustainability?

It is widely agreed in the literature that Sustainability is a balanced integration of economic performance, social inclusiveness and environmental resilience, to the benefit of current and future generations (Brundtland, 1987; Elkington, 1999). Detrimental impacts of many technological trajectories upon natural resources have raised questions about whether present prosperity trends can be expanded – or even maintained – in the future (Clark and Crutzen, 2005). This term is the basis for discussions on alternative directions of sociotechnical progress and on shared responsibilities both in defining societal goals and on how to better pursue them (Leach et al., 2007). Tensions within the literature lie mostly on what to prioritise. Sustainability concerns have entered both into the agendas of policymakers and industry managers since the second half of the 20th century. Although the term has been since interpreted very differently, its diffusion is attributed to environmental discussions. Since the 1960s, science has identified a series of global-scale environmental risks, such as the ozone depletion, climate change, biodiversity loss, and the alteration of the nitrogen cycle. These risks have resulted from extensive anthropogenic activities and fuelled by rapid technological developments beyond "the wildest Neolithic dreams" (Grey, 1993:464). Furthermore, these emerging sustainability risks challenge our former understandings of development patterns as purely positive and question our ability to sufficiently account for the scarcity of environmental resources (Cohen, 1997).

The identified threats initiated international discussions on the complex and dynamically interconnected nature of the environment, society and the economy (Kates et al., 2005). These discussions started to systematically challenge prevailing economic frameworks and instead envisioned new frameworks integrating the social, economic and environmental dimensions as continuously and cumulatively affecting one another (Mckelvey, 2002).

It is consensual that sustainable development initiatives should be planned and coordinated on a local level because requirements and opportunities vary among regional contexts. The definition of sustainable development is, therefore, deliberatively vague (O'Riordan, 1993). This vagueness accommodates a variety of understandings and expectations for progress and allows for heterogeneous responses to the diversity and complexity of challenges faced by humans around the world (Kates et al., 2005).

The verb sustain means to maintain certain features of an instance over time. The meaning of the noun development can vary depending on values, interests and disciplinary lenses (National Research Council, 1999). The term can be interpreted in different ways and justify commitments based on various motivations, from targeting inflation to controlling pandemics. These are, in fact, some of the main sources of tension in decision-making. Given that resources are limited and problems are complex, addressing

Table 2
Content and references for the six main research areas.

Category	What does it include?	References
1. Governance of Innovation Systems	Systematic stimulation of innovation and its link to macroeconomic performance	(Amsden, 2002; Carlsson et al., 2002; Chang, 2002; Freeman and Louçã, 2001; Freeman and Perez, 1988; Freeman and Soete, 2000; Lanahan and Feldman, 2015; Lundvall et al., 2009; Martin, 2012; Martin et al., 2012; Mazzucato, 2013)
	Public governance frameworks of science, technology, and innovation systems	(Cooke et al., 1997; Doloreux and Parto, 2005; Freeman, 1995; Furman et al., 2002; Geels, 2004; Lundvall et al., 2002; Malerba, 2004, 2002)
	Institutional theories influencing Innovation Systems	(Hodgson, 2005; North, 1990)
	Concepts focussing on the peculiarities of innovation-driven development in low and middle-income regions	(Abramovitz, 1986; Fagerberg, 1994; Gerschenkron, 1962; Viotti, 2002)
2. Innovation Management	Resources, competences, and dynamic capabilities, routines, and learning of companies	(Dosi et al., 2000; Leonard-Barton, 1992; Meyer and Utterback, 1993; Nelson and Winter, 1982; Penrose, 2013; Teece et al., 2008)
	R&D management and new product introduction	(Clark and Fujimoto, 1991; Roussel et al., 1991)
	Multifunctional and systemic approaches of innovation and technological management	(Goffin and Mitchell, 2010; Gregory, 1995; Phaal et al., 2001; Tidd, 2001; Van de Ven et al., 1999)
	Concepts clarifying and distinguishing innovation in processes, products, services, and business models	(Barras, 1986; Chesbrough, 2010; Eisenhardt and Tabrizi, 1995; Ettlie and Reza, 1992; Gallouj and Weinstein, 1997; Hipp and Grupp, 2005; Utterback and Abernathy, 1975; Zott et al., 2011)
	Collaborative frameworks for generation and diffusion of open innovation, triple helix, and user innovation	(Chesbrough, 2003; Leydesdorff, 2000; Mortara and Minshall, 2011; Pisano and Verganti, 2008; Von Hippel, 2001)
3. Sustainable Development	Distinctions between Anthropocentric and Ecocentric approaches	(Grey, 1993; Morton, 2007; White, 1967)
	Theories on growth and environment trade-offs, e.g., degrowth, growth limits, steady-state, and growth-fetish,	(Daly, 1991; Daly and Townsend, 1993; Hamilton, 2004; Jackson, 2009; Kallis, 2011; Meadows et al., 1972)
	International sustainable governance discussion on environmental, social, and economic dimensions	(Brundtland, 1987; Clark and Crutzen, 2005; Elkington, 1999; Kates et al., 2005; Middleton and O'Keefe, 1993; O'Riordan, 1993; Sachs, 2015)
	Different perceptions of what is to be sustained, what is to be developed and what is attainable	(Fowke and Prasad, 1996; Kates and Parris, 2003; Leach et al., 2007; National Research Council, 1999; UNCED, 1992; United Nations, 2015; Williams and Millington, 2004)
	Vulnerability, resilience and complexity of social-environmental systems	(Kharrazi et al., 2016; Meerow and Newell, 2015; Rockström et al., 2009; Stirling, 2014; Turner et al., 2003) (Kharrazi et al., 2016; Meerow and Newell, 2015; Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falke, 2009; Stirling, 2014; Turner et al., 2003)
	Sustainable corporate strategy, e.g., sustainable industries, CSR, shared value, bottom of the pyramid, and circular economy	(Cohen, 2006, 1997; Crane et al., 2014; Evans et al., 2009; Jänicke and Jacob, 2006; Mcwilliams, 2016; Porter and Kramer, 2011; Prahalad, 2004; Prahalad and Hart, 2002; Webster, 2015)
	Sustainability-driven innovation, e.g., eco-innovation and social innovation	(Basu et al., 2013; Ekins, 2011; Esty and Winston, 2009; George et al., 2012; Graddy-Reed and Feldman, 2015; Hart, 2000; Hart and Milstein, 2003; Jordan and Lenschow, 2008; Kemp, 1994; Kemp and Pearson, 2007; Lafferty and Hovden, 2002; Nakata and Weidner, 2012; OECD, 2011; Prahalad et al., 2012; Radjou et al., 2012; Schiederig et al., 2012; Seyfang and Smith, 2007)
4. Public Understanding of Science, Technology and Society	Social construction of knowledge	(Jasanoff, 2009; Latour and Woolgar, 1986; MacKerron and Berkhout, 2009; Miller, 2005; Millstone, 2007; Pestre, 2008)
	Plurality and democratic accountability in policy-appraisal and mechanisms for appraising different dimensions of uncertainty	(Beck, 1999; Ezrahi, 1990; Funtowicz and Ravetz, 1995, 1990; Jasanoff, 2010, 2009; Leach et al., 2005; Smith and Stirling, 2007; Stirling, 2007, 2003; 2014, 2009; Thompson et al., 2007; Wynne, 1992)
5. System Thinking and Design	Ontologies of knowledge-about-system and epistemologies of system thinking and complex system theory	(Cabrera, 2006; Capra, 1983; Forrester, 1961; Kauffman, 1995; Meadows, 2008; Mingers and White, 2009; Senge, 1990)
	System design for sustainability	(Blizzard and Klotz, 2012; Ceschin and Gaziulusoy, 2016; Charnley et al., 2011; Gaziulusoy and Brezet, 2015; Seiffert and Loch, 2005)
6. Wide-scale Changes of Sociotechnical Systems	Technological paradigms and revolutions, dominant design, sociotechnical regimes and their transformation/lock-ins	(Abernathy and Utterback, 1978; Arthur, 1989; Bijker, 1995; Dosi, 1982; Kuhn, 1996; Mckelvey, 2002; Nelson and Winter, 1982; Perez, 2002; Stegmaier et al., 2014; Van de Poel, 2000; Von tunzelmann et al., 2008)
	System innovation, sociotechnical governance, transition and strategic niche management, and complexity governance	(Borrás and Edler, 2015; Ekins, 2011; Elzen et al., 2004; Kemp et al., 1998; Kivimaa and Kern, 2016; Mokyr, 1990; Rotmans et al., 2001; Schot and Geels, 2008; Smith and Raven, 2012; Sushandoyo and Magnusson, 2014; Teisman et al., 2010)
	The roles performed by different agents, such as companies, governments and civil society in sustainability transitions	(Berkhout et al., 2004; Coenen et al., 2012; De Haan et al., 2014; Farla et al., 2012; Geels, 2010, 2005, 2002; Geels and Schot, 2007; Jørgensen, 2012; Kemp, 1994; Loorbach, 2010; McDowall, 2012; Penna and Geels, 2012; Rip, 2006; Shove and Walker, 2010; Smith et al., 2010, 2005; Smith and Stirling, 2007; STRN, 2010; Turnheim et al., 2015; Wittmayer and Schäpke, 2014)
	Mechanisms to assess and influence transitions, e.g. backcasting, scenario building, urban metabolism	(De Jouvenel, 2000; Dreborg, 1996; Durance and Godet, 2010; Holmberg and Robert, 2000; Pincetl et al., 2014; Rip and Schot, 1996)

sustainability requires comparing and deciding what co-existing goals will be prioritised; what responsibilities will be assigned to each stakeholder; and what means can be deployed to reach the goals.

However, the nature of goals set by different narratives of sustainable development clearly relies on their dominant interests, which are essentially plural (Clark and Crutzen, 2005). Instead of merely setting common goals, the literature on public

understanding of science and technology emphasises that sustainability widens the scope for multiple expectations on what is to be developed, what is to be sustained, for how long, and for the benefit of whom (Jasanoff, 2010). It also illustrates the extent of our ignorance whereby policy interventions are gradually seen as path-dependent and adaptable experiments. This in effect paves a path from cognitive predicaments, e.g., uncertainty and incommensurability, to challenges associated with agency behaviour, intentionality upon the wide range of responses to sustainability challenges (Stirling, 2014).

3.1.2. Why sociotechnical systems?

In our sample, there were many sources of agreement. Several studies on sociotechnical change for sustainability refer to environmental threats, e.g., climate change, biodiversity loss, and water scarcity, and suggest that relevant solutions cannot be achieved only through the incremental development of clean technologies. In this avenue, social, economic or political aspects, such as unsustainable consumption, financial crises, and public budget overruns, are sometimes seen as resulting factors of technological lock-ins and path-dependency (Smith et al., 2005; Markard et al., 2012). They thus indicate the need for substantive transitions, with deep structural changes in sociotechnical systems (Berkhout et al., 2004; Smith et al., 2010).

There are, nonetheless, profound sources of tension in the perceptions of the role of science, technology and innovation among scholars and policy makers, given the following four reasons.

Firstly, there are discussions on the way past technological trajectories led to unintended consequences. Since the industrial revolution, new technological paradigms have been emerging, which have changed human behaviour and wellbeing, consumption preferences, industrial infrastructure, and political frameworks. The literature also recognises that companies are increasingly under pressure to create innovations capable of capturing new opportunities to drive profits for shareholders and ensuring longevity (Hart and Milstein, 2003). However, the benefits of technological development have not reached all stakeholders equally while the environment has been degraded considerably and is compromising the long-term life-support systems for human existence (Sachs, 2015).

Secondly, progress in science, technology and innovation provided the knowledge base and tools to assess unintended consequences, to appraise desired futures and to reveal potential alternatives. Technical knowledge and technological tools have been critical to inform decisions aimed at shifting sociotechnical progress towards more sustainable directions (Beck, 1999).

Thirdly, innovations are increasingly the main source of hope in finding alternative development models. Changing the existing unsustainable paradigms requires efforts from different agents to generate and diffuse products, processes, services, technologies, business models and policies capable of simultaneously benefitting the economy, the environment, and the society (Kemp et al., 1998; Hart and Milstein, 2003; Jordan and Lenschow, 2008). As there are various sources of stimuli to the generation and diffusion of sustainable innovations, it becomes critical to understand how innovation management (and governance) can steer innovative performance towards more sustainable directions. However, while many implemented efforts have emphasised technical solutions, rather than social and political mobilisation (Clark and Crutzen, 2005), others claim that a successful transition towards sustainability could be achieved with existing technologies (National Research Council, 1999). Therefore, they believe that capabilities, social learning, and political willpower promoting viable and technologically feasible alternatives should be prioritised.

Fourthly, the scope of analysis has broadened from technical to sociotechnical or societal systems in the literature. Technical systems revolve around artefacts, and indirectly recognise the role of social dimensions in the generation and diffusion of technologies. Differently, sociotechnical systems are composed by several technologies entrenched with social, political and economic dimensions (De Haan et al., 2014).

3.2. What?

In the following, we describe factors, variables and concepts widely used to describe sociotechnical system change, before we present what system changes qualify as sustainable.

3.2.1. What is a sociotechnical system?

It is very consensual within literature that innovations are not isolated events: they should be seen in the light of co-evolving systems (Freeman and Soete, 2000). The most important property of system thinking is that a system is more than the sum of its parts, and these parts are interconnected into complex structures (Meadows, 2008; Seiffert and Loch, 2005). The basis of system thinking is thus seeing “wholes”: investigating entire systems within a boundary, understanding their components, functions, and interconnections (Senge, 1990).

It is widely accepted that systems are characterised by feedback loops, self-organisation, and hierarchies. Feedback loops are closed chains of causal connections that can be either sources of (in)stability, (dis)continuity or resistance to change. Self-organisation describes the ability of systems for self-structuring to learn, diversify, and become more complex over time. However, self-organisation also tends to create resilience towards radical changes, as systems tend to keep coherence in their functions. Systems often involve hierarchies too, with arrangements between systems, subsystems and their components. The trade-off between autonomy and coordination in hierarchical systems is rather complicated, potentially constraining or fostering subsystems. It is also important to highlight that, as resilience, self-organisation, and hierarchy are the main reasons dynamic systems work so coherently, intervening in these properties can drastically influence the system's ability to function (Blizzard and Klotz, 2012; Meadows, 2008).

The literature presents some sources of tension, in what regards distinct analytical characteristics and the proposition of different pathways. This includes, for example, regime transformation (Van de Poel, 2000), technological revolutions (Perez, 2002), system innovation (Elzen et al., 2004) and sociotechnical transitions to sustainability (Geels and Schot, 2007). However, despite conceptual specificities, these perspectives share the understanding that systems are changed through interconnected changes within self-reinforcing domains of technology, the economy, institutions, behaviour, and cultural systems (Rotmans et al., 2001).

Furthermore, using a sociotechnical system as a unit of analysis draws from several converging scholarly contributions, including dominant design (Utterback and Abernathy, 1975), technological paradigms (Dosi, 1982), and technological regimes (Nelson and Winter, 1982).

A dominant design is what provides a reference outlook for engineers, designers and technologists, signalling the basis for further progress (Utterback and Abernathy, 1975). These outlooks enable continuous technological development in certain sociotechnical clusters. They are composed by beliefs, expectations and knowledge bases that illustrate certain opportunities, while simultaneously hindering the development of other potentially viable alternatives (Kemp et al., 1998).

It is widely accepted in the literature that sociotechnical evolution reflects a process of ongoing reproduction that incorporates

cumulative, gradual, and self-reinforced characteristics (Kemp, 1994; Shove and Walker, 2010). This idea was further elaborated in the concept of technological paradigms (Dosi, 1982), which describes core technological frameworks that guide innovative activities of industries. With a similar yet broader scope, the concept of technological regimes was initially framed by Nelson and Winter (1982) and has highly influenced studies on sociotechnical system change. Similar to "dominant design", this concept recognises the stable and incremental nature of problem-solving, also introducing boundaries for the expected direction of technological progress (Kemp, 1994). However, when new technological trajectories emerge, agents start exploring different solutions. This is done through negotiations and coalition building (Geels and Schot, 2007), eventually reaching a dominant interpretation based upon goals, strategies, heuristics, tacit and codified knowledge, to cite just a few (Bijker, 1995).

The term regime has also been widely used in sustainability transitions theory because it does not exclusively focus on paradigms or systems. It also incorporates the idea of 'rules' from institutional theories (Hodgson, 2005; North, 1990). A technological regime encompasses sets of rules – for example, from the market, heuristics of engineering communities, user requirements, laws, and policy framings. These guide the innovative activities that companies are likely to undertake, the solutions that will be prioritised and the strategies of a vast array actors (Kemp et al., 1998). The concept of regime has helped academics in the field to understand why some radical technological alternatives are not explored, especially when requiring substantial contextual changes, and why most innovative efforts are aimed at incremental changes instead of regime transformation.

This notion of regimes was broadened by scholars analysing contributions of a diverse set of stakeholders to technological progress (Bijker, 1995). The resulting concept of sociotechnical regimes combines the dynamics of variation, selection and retention, which is highly accepted within our sample.

Variation refers to expectations, visions and cognitive guidance for intentional and deliberate innovative efforts. Selection occurs due to the context, which incorporates not only markets, but also regulations, social behaviour, industrial structures, knowledge, and cultural influences. Dominant technologies and infrastructures thus act as selection pressures through articulated standards and arrangements imposed on sociotechnical features. Guiding principles and cognitive processes favour incremental developments over paradigm shifts, and dominant consumer preferences stabilise market institutions, supply and demand, prices, and user behaviour (Geels, 2002; Nelson and Winter, 1982). Retention provides and reinforces the rules to maintain working solutions, stabilising technological trajectories through, for example, cognitive routines of engineers (Nelson and Winter, 1982), regulations and standards, adaptation of social lifestyles, and infrastructure and competencies (Geels and Schot, 2007). The more a technology is adopted, the more the user familiarises itself with it; this stimulates further improvements and entrenchment into the economic system (Smith and Raven, 2012).

Academics also agree that sociotechnical regimes are neither fully deterministic nor completely behavioural. Agents are capable of interpreting, applying and negotiating rules they do not fully control (Geels, 2010). By applying the concept of sociotechnical regimes, it is then possible to realise that the prevailing unsustainable technologies and social habits can be interpreted as embedded and self-reinforcing systems, opening up scope to questions of 'how' to steer change towards more socially desired directions.

3.2.2. What is sustainable?

The analysis of sociotechnical systems often implies the ultimate idea that there are mutually reinforcing and highly institutionalised processes in sociotechnical regimes. This makes it difficult for sustainable innovations to succeed against the existing unsustainable alternatives, consequently constraining radical structural changes. These analyses are often methodologically based on historical analysis and case studies.

The conceptual responses to sustainability challenges represent great sources of tension They can range from confrontational to pacifying approaches. Confrontational concepts tend to be anchored on the prioritisation of "sustaining" instead of "developing", mostly emphasising trade-offs between the economy and the environment. These approaches lay different emphasis on the extent of confrontation or resistance to be employed, and encompass notions like Steady-State (Daly and Townsend, 1993), Degrowth (Kallis, 2011), and Prosperity Without Growth (Jackson, 2009). Alternatively, pacifying approaches aim at harmonising divergences and exploring win-win situations. Different value opportunities are uncovered that promote soothing bridges and nurture reflexivity about desired directions and potential futures (Evans et al., 2009; Hart and Milstein, 2003).

Yet, despite diversity, the emphasis lies on some major areas of agreement. A literature review conducted by the Board on Sustainable Development of the United States National Research Council (National Research Council, 1999) found major categories that are still very up-to-date. Under the heading of "what is to be sustained" they found 3 categories: life support systems, nature, and communities. A substantial part of the literature highlights sustaining life-support systems, by analysing natural resources as necessary conditions to the survival of humankind. In contrast, a minority would rather defend nature's value for its intrinsic qualities, instead of what it provides to humans. A third stray in the literature also covers the importance of sustaining livelihoods, cultural diversity and threatened communities (Clark and Crutzen, 2005; Kates and Parris, 2003).

According to the same study, there are also three areas of agreement about "what is to be developed": economy, people and society. The first aggregates much of the traditional literature on economic development, focussing on wealth, desired consumption, productive sectors and employment. The shift to human development falls under the second category, describing inequality, education, equal opportunities and other better quantifiable targets, such as life expectancy and infant mortality rates. The Board also identified goals centred on broader concepts of life in society, with a focus on community ties, national security, institutional change, social capital, and well-being (Kates and Parris, 2003).

Furthermore, authors tend to prioritise specific sociotechnical systems, sectors or even sets of infrastructures such as transportation or agricultural systems. In a literature review conducted by Markard et al. (2012) on sustainability transitions, between 1990 and 2011, the energy sector and its technologies represented by far the most dominant topic, amounting for 36% of all papers, followed by studies covering transportation (8%), water and sanitation (7%), and food (3%). Besides, the analyses of sociotechnical systems depends on system boundaries, that are essentially arbitrary. The definition of such boundaries varies according to goals, challenges, actors, networks, geographical location, generalisability, and analytical feasibility. A great part of the art of analysing and designing systems therefore lies on setting appropriate boundaries for each purpose. However, as described by Meadows (2008), we are too attached to our accustomed boundaries, such as, national, ethnic, or income boundaries. These conventional boundaries have,

in fact, greatly influenced the literature. That is the case, for example, in literature on 'National Innovation Systems' and 'Sectoral Innovation Systems'.

Another source of agreement is the importance of analysing structures, agents, and processes that reproduce or cause breakthroughs in sociotechnical systems. Some unsustainable sociotechnical systems are more embedded than others, as they enjoy larger economic significance, supportive infrastructures, political legitimacy, and institutional support than the relevant alternatives (Smith and Stirling, 2007). For this reason, several authors also emphasise the importance of nurturing innovative niches. These are particularly relevant because sustainable innovations, even more than the traditional ones, can be referred to as 'hopeful monstrosities' (Mokyr, 1990:291). They can be hopeful, as they might contribute to a desired future while they can also be monstrous because they might perform crudely in their early stages (Kemp et al., 1998).

This is, in fact, widely described as a pivotal problem for sustainable innovations with a radical impact potential, as they can get stuck while aiming at trespassing a metaphorical 'valley of death' between generation and wide diffusion (Schot and Geels, 2008). Therefore, as sociotechnical regimes benefit from accumulated privileges that act as a form of protection of unsustainable alternatives, radical innovations often struggle to emerge to the market and compete with incumbent alternatives. Niches can nonetheless shield sustainable innovations, holding at bay certain selection pressures from the regime in order to protect desired alternatives (Geels and Schot, 2007; Smith and Raven, 2012).

3.3. How?

A pervasive challenge is to understand connections between variables, delineating correlation or introducing causality influencing sociotechnical system change for sustainability. The most notable ones refer to understanding how sustainability can be fully pursued, as well as the extent to which sociotechnical change is (and can be) susceptive to deliberation.

3.3.1. How to steer sociotechnical change?

It is highly consensual that the capacity of generating and diffusing innovations depends on the agency of different players, such as companies, governments, civil society or even collaborative networks. The literature thus tends to investigate the scope of the performance of each agent in influencing innovative performances and consequently sociotechnical system change.

Innovation management of companies, for example, covers multifunctional components and interactions between strategic choices, corporate culture, human resources, and operations (Tidd, 2001). Companies are central change agents, which are integrated into networks with other actors, such as governments, civil society, and other users of their products and services. They are thus influenced by other actors and by institutional arrangements in ways that can either constrain or enable innovations to arise and diffuse (Lundvall et al., 2009).

However, when the unit of analysis shifts from an innovation or from the innovating agent to a sociotechnical system, the understanding of "how" leads to many new questions. These questions include for example: How to define the boundaries of a system and what systems should be prioritised? How to steer (or adapt to) ongoing systems change? How to operationalise change and who should be involved? How to coordinate many agents? How should each agent behave? How are they accountable for the desired change?

In fact, by emphasising sociotechnical systems as units of analysis, the literature embarks on a more open-ended journey than when analysing innovative performance, opening up room for interpretive tensions. The analytical focus lies "on processes such as learning, radical innovation, experimentation, searches for new paths, participatory approaches, multi-actor interactions, selection processes, reactions, and network evolution" (STRN, 2010:5). Since sociotechnical systems are very complex, and do not have owners, the idea of managing or governing sociotechnical systems is often framed as reflexive, evolutionary, and adaptive processes (Smith and Stirling, 2007; Voß et al., 2009), maintaining the objective of developing instrumental models to steer ongoing change (Smith et al., 2010; Markard et al., 2012). These ideas received great contributions, for example, from complex systems theory (Kauffman, 1995), innovation governance (Smith et al., 2005), resource-based approaches of management (Penrose, 2013; Teece et al., 2008), and some streams of innovation studies – e.g., innovation systems (e.g. Freeman, 1995) and technological regimes (Nelson and Winter, 1982). Furthermore, the idea of distributed governance arises as the means of covering different societal actors, their distinct patterns of governance, and their resulting interplay of activities. This also leads to a better understanding of the conflicts inherent to sociotechnical change, the influence of politics of knowledge, and the different forms that power affects decision-making (Jasanoff, 2010; STRN, 2010).

3.3.2. How to change sociotechnical systems towards sustainability?

A major source of agreement within the literature consists of fostering the adaption of sustainable solutions to replace or reshape current sociotechnical systems to achieve environmentally, socially and economically desirable outcomes (Kivimaa and Kern, 2016; Schot and Geels, 2008; Sushandoyo and Magnusson, 2014). These concepts either focus on innovation or system change. The ones focussing on innovations or innovative agents emphasise sustainable processes, products, services or business models, capable of replacing unsustainable alternatives. This includes, for example, concepts of eco-innovation (Esty and Winston, 2009; Hart, 2000; Kemp and Pearson, 2007; OECD, 2011), innovation for the bottom of the pyramid (Prahalad and Hart, 2002; Prahalad, 2004; Prahalad et al., 2012), grassroots innovation (Seyfang and Smith, 2007), and frugal or inclusive innovation (George et al., 2012; Radjou et al., 2012; Basu et al., 2013).

Concepts focussing on wide-scale system change focus on the directionality, intensities, extents, and reasoning behind these changes. Since they are subjective and depend on multiple ontologies of "what the world is" and "what the world will likely be", as well as normativities of "what the world should be" (Geels, 2010), many studies emphasise democratic and deliberative governance as important for promoting greater appreciation of plurality and human intentionality upon the multiple (and often contending) viable pathways for sociotechnical progress (Leach et al., 2007).

Literature converges in the description of the importance of influencing selection pressures of sociotechnical regimes, as well as the coordination of resources to better adapt, react, or anticipate to such pressures. Selection pressures include political, social and economic developments, and pressures that "bubble up from below, from innovative niches that are not yet so established as to constitute a regime" (Smith et al., 2005:1495). The Multi-Level Perspective, for example, describes the importance of destabilising undesirable sociotechnical features, while building up momentum for niche-innovations (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010).

It also seems consensual that the ability of influencing sociotechnical change towards sustainability is also diffused among a

vast array of actors. Most concepts covering wide-scale changes, like Strategic Niche Management (Schot and Geels, 2008; Smith and Raven, 2012; Sushandoyo and Magnusson, 2014), Transition Management (Rotmans et al., 2001; Loorbach, 2010; McDowall, 2012), or the Multi-level Perspective of Sustainability Transitions (Geels, 2002, 2010; Smith et al., 2010), argue that different agents can assume more dominant roles to influence, manage or govern transitions, including governments and policy-makers, companies, non-governmental organizations, and entrepreneurs. However, all of them also make explicit that deliberate intents of transitioning to more sustainable directions are not purviews of single actors. Instead, they are collective endeavours requiring a certain degree of coordinated action (Kemp et al., 1998).

A challenge is, therefore, to bring these concepts to action, providing practical guidelines on the activities and roles that can be performed by different actors. Many strategies, instruments and tools have emerged to address these challenges. The literature on Sustainability Transitions, for example, indicates clusters of activities capable of unsettling regimes and translating sustainable alternatives from the fringe to the mainstream (STRN, 2010). Among these strategies and instruments are: backcasting (Dreborg, 1996; Holmberg and Robert, 2000) and scenario-building (De Jouvenel, 2000; Durance and Godet, 2010), as well as conceptual frameworks such as Constructive Technology Assessment (Rip and Schot, 1996), Transition Arena's (Loorbach, 2010), Complexity Governance (Teisman et al., 2010), and Strategic Niche Management (Kemp et al., 1998; Schot and Geels, 2008; Sushandoyo and Magnusson, 2014).

4. Discussion: what are the theoretical foundations?

This section discusses the theoretical foundations of sociotechnical systems change for sustainability. In other words, the dominant understandings of 'what things are' and 'what things should be' within the literature. We identified fourteen foundations, which are summarized in Table 3. Among them, two describe the underlying motivations that are justifying the research questions and the selection of variables that scholars have been investigating, i.e., the Why?, which are essentially normative; six describing factors widely considered as part of the explanation of the phenomena, i.e., the What?; and six that describe connections, causality patterns, and possibilities of steering sociotechnical progress towards sustainable outcomes, i.e. the How? Together, these three dimensions constitute the foundations of sociotechnical system change for sustainability. It is important to stress that foundations are essentially intertwined; refuting one of them might lead to changes in others.

A foundation in the literature is the interpretive flexibility of sustainability discourses. This is connected to the diversity of interpretations of both the terms 'sustainable' and 'development'. However, only a small subset of options is assumed to be currently investigated and decision-making seems to be shaped by power relations. Knowledge is also seen as socially constructed, thus affecting the prioritizations of certain systems and goals over other alternatives. These foundations are connected to the observation that development goals and steering mechanisms of sociotechnical systems are socially negotiated through plural appraisals and deliberations and that action is coordinated among a vast array of agents continuously adapting to changes in their respective contexts.

Another underlying motivation consists of the investigation of wide-scale changes of sociotechnical systems towards more sustainable outcomes. Sustainable innovations alone may influence sociotechnical systems and cooperation seems to be critical for realising opportunities and improving results. Nevertheless, each agent may have different priorities and the analytical foci often lie too narrowly on their efforts in promoting win-win situations for themselves and for their stakeholders.

Table 3
The foundations of sociotechnical system change for sustainability.

Category	What does it include?
Why?	Sustainability should have flexibility in its interpretation to justify different interests and adapt to different contexts
	Democratic accountability is critical to assess expectations and deliberate over the multiple understandings and aspirations for progress
What?	There are multiple interpretations of what is to be sustained and what is to be developed. There are multiple goals and pathways for development, but only a subset will be fully pursued. Knowledge is also socially constructed and politics of power influence why some systems or certain sustainability goals tend to be prioritised
	When the unit of analysis lies on sociotechnical systems, the analysis involves a wide range of actors, and no agent has full accountability nor ownership of sociotechnical systems
	Sociotechnical systems are composed by a variety of co-evolving components, functions and interconnections, and are characterised by feedback loops, self-organisation, and hierarchies
	Boundaries are arbitrary for analysis
	Institutions shape solutions that will be prioritised, the strategies of a vast array of actors, and the heuristics of problem-solving
	System change happens through a combination of variation, selection, and retention. Analysis revolves around the generation and diffusion of innovations capable of replacing predominant and unsustainable alternatives
How?	Diversity and plurality are critical, both to open up and to close down appraisal over multiple alternatives
	Incremental changes will not suffice. Wide-scale changes of sociotechnical systems should be at the core of sustainability ambitions
	Long-term governance, with stakeholder engagement, is the standard approach to deal with wide-scale system-level changes
	Governance or management has dimensions that can be controlled (e.g. internal aspects of management or governance), others that can only be influenced (e.g. knowledge base), and exogenous features they react upon (e.g. demography)
	Although boundaries of systems are analytically flexible, agency tends to follow conventional boundaries
	Cooperation is critical, but priorities are defined by each agent
	Mostly seeking win-win situations for the economy, environment, and society

Their impacts are therefore uncertain, may be socially exclusory, and entail unintended consequences. Many studies discuss the importance of using sociotechnical systems as a unit of analysis, rather than single solutions or actors. This meso-level oriented analytical lens allows the examination of a wide range of components and connections of the system, including several actors integrated in webs of sociotechnical change. In this picture, several agents influence sociotechnical systems, but none are fully responsible, nor accountable for the desired change. This may justify why most studies set long-term governance objectives, through the coordination of multiple stakeholders, as the standard approach to deal with wide-scale system-level change.

When deepening the analysis of systems, it is revealed that sociotechnical systems are composed by a variety of co-evolving components, functions, and interconnections. These systems are characterised by feedback loops, hierarchies, and self-organising patterns. These characteristics attribute complexity both to the investigation and the potential steering efforts of sociotechnical systems. They present embedded characteristics and lock-ins into certain technological trajectories, but their components, functions and interconnections may be unpredictable.

As a result, actors who try to manage or govern sociotechnical system change may simultaneously face internal levers (e.g. aspects of a company or a public body upon which they have agency);

leverage points to influence or nudge systemic change (e.g. knowledge base, political framings, social behaviour, and industrial structures); and exogenous aspects that restrain their scope for action and upon which they can only react (e.g. environmental or demographic shocks).

The other implication of setting meso-oriented analytical lenses is that systems are arbitrarily bounded when analysed, in order to fully examine characteristics and evaluate possibilities of steering ongoing changes. They are often framed according to goals, interests and viabilities to appraise and act upon. However, the scope for action of some agents often lie within pre-established ones. Taking a federal government as example: agency lies on the national borders. Similarly, a company has its agency limited by a conventional boundary, since it is an organizational entity, legally defined by ownership and composed by an interconnected pool of resources.

Furthermore, system change happens through a combination of variation, selection and retention. Although most studies focus on variation, it seems clear that evolutionary dynamics of sociotechnical change derive from the interplay of these three features. The characteristics and components of sociotechnical systems shape solutions that have higher potential of succeeding, the strategies of each agent, and the heuristics to solve problems and adapt to ongoing change.

5. Opportunities for theoretical contribution and final remarks

Section 5 scrutinised the dominant foundations guiding theoretical development in the field to date. By deconstructing theory to pinpoint its foundations, it becomes possible to take more informed decisions on how to contribute to further theoretical development.

Contributing with a new normativity can change the motivations of research in the field, while an ontology, without necessarily challenging the motivations underlying their investigation, offers new lenses for interpreting phenomena. A new ontology is more academically defensible than a new normativity, since the latter is essentially argumentative, resonating more with values, interests and institutional commitments of a wide range of scholars. For example, when Hardin (1968) implied that 'social injustice is preferable to environmental ruin', he was raising a new normativity, based on his widely diffused ontology of the 'tragedy of the commons'. If his normativity, instead of the renowned triple bottom line (Elkington, 1999), had become widely diffused and accepted by scholars, the theory would have had developed very differently in Sustainability studies.

Based on reflections upon the 14 foundations revealed in this paper, this section introduces and illustrates 3 possibilities for future contributions. These include: 1) how to fill existing gaps without questioning the foundations; 2) how to rebut the foundations by questioning their validity; and 3) how to build theory by creating new foundations that can either substitute or complement currently existing foundations.

5.1. Gap filling

Opportunities for gap filling mostly derive from questions on contextual influences (i.e. Where, Who and When). They tend to be ontological contributions, incrementally adding to the existing theoretical understandings and without challenging the existing theoretical foundations.

For example, one of the foundations described in Section 4 is the existence of 'multiple interpretations of what is to be sustained and what is to be developed'. There are several potential questions that can arise for Where, Who, and When, such as the ones below:

- Who: how different are the interpretations of businesspeople and policymakers?
- Where: how do these interpretations differ across low, middle, and high-income countries?
- When: are these interpretations changing since the publication of the Brundtland (1987) report?

These kinds of questions aim at better qualifying the circumstances, contingencies, and contexts in which the theoretical foundations are manifested, hence contributing to filling gaps within the theory.

5.2. Rebutting existing foundations

It is possible to refute the foundations listed in Section 5. This process is essentially deductive, raising hypothesis on the validity of an ontology or the desirability of a normativity. Since Why foundations are more argumentative, there is scope both for normative and ontological rebuttals, whereas What and How are likely ontological. Boxes 1, 2 and 3 illustrate how new contributions can arise from rebutting existing foundations.

5.3. Creating new foundations

New foundations can either substitute or complement the ones listed on Section 5. As discussed by Whetten (1989), potentially radical contributions often arise from novel interpretations of Why, What and How, reframing interests, goals, motivations, or the analytical principles and lenses used to investigate empirical phenomena.

As demonstrated in Boxes 4 and 5, new contributions can arise when analysing the implications and resulting complications of

Box 1

Why foundation: 'sustainability should have flexibility in its interpretation, justifying different interests and adapting to different contexts'.

Examples of Rebuttals: is interpretive flexibility desirable? Should we prioritise specific goals, such as eradicating hunger, instead of open-ended goals? Are academics converging towards similar understandings, independently of contexts? Are academics progressively interpreting sustainability exclusively as environmental performance?

Box 2

What foundation: 'when the unit of analysis lies on sociotechnical systems, the analysis involves a wide range of actors, and no agent has full accountability nor ownership of sociotechnical systems'.

Examples of Rebuttals: are some agents entitled to have full accountability and ownership of sociotechnical systems? Are multiple agents, in fact, involved in sociotechnical systems change, or is change mostly led by a single one?

Box 3

How foundation: 'mostly seeking win-win situations for the economy, environment, and society'.

Example of Rebuttals: are the solutions really a win-win in all three dimensions, or is that just an encouraging, pacifist discourse that has become institutionalised? What are the trade-offs that have been largely ignored under such false pretences?

Box 4

Existing foundation: 'analysis revolves around the generation and diffusion of innovations capable of replacing predominant and unsustainable alternatives'.

Implication: analytical focus lies on the generation and diffusion of products, processes, services or business models, which are capable of replacing the predominant unsustainable alternatives in the marketplace.

Complication: as innovations inevitably revolve around commercialization, roles of a diverse set of interconnected agents (e.g. companies, governments, and individuals) are investigated accordingly. As a consequence, analysis of sociotechnical system change tends to be market-centred.

Alternative investigation: what steps individuals and organizations can take at the micro-level that may not materialize through the marketplace, but which may be capable of changing sociotechnical systems?

Box 5

Existing foundation: 'long-term governance, with stakeholder engagement, is the standard approach to deal with wide-scale system-level changes'.

Implication: a wide range of possibilities needs to be assessed, various agents coordinated, and multiple actions planned and adapted to changing contexts.

Complication: the speed and scope for tackling complex sociotechnical problems are limited by agency failures, resulting from the coordination of multiple agents for deliberation.

Alternative investigation: what purposeful actions conducted by self-entitled agents can be pursued to leverage wide-scale systems change?

existing foundations; hence leading to the proposal of alternative research avenues.

Furthermore, the process of creating new foundations often involves overlapping the existing ones with novel empirical insights. For example, Bitcoin bypasses sovereignty and traditional boundaries of governance. It is not an innovative product, process, service or business model generated and diffused by companies; its social, environmental and economic outcomes are contested; and it is derived from a purposeful (and anonymous) action happening 'here and now' which may deeply change sociotechnical systems. It strays deeply from some foundations presented in this work. Hence, by analysing this phenomenon in contrast to the dominant foundations, novel and potentially disruptive contributions can arise, complementing or even substituting the existing ones.

5.4. Final remarks

This work has systematically exposed and discussed 14 foundations that shape how we understand sociotechnical system change for sustainability. These foundations influence both what system change is perceived as desirable and as attainable; as well as how to navigate between all the coexisting pathways, trade-offs, and complexities of the three dimensions of sustainability. By identifying the theoretical foundations, we illustrate the most up-to-date theoretical developments and concomitantly pinpoint a few opportunities for future contributions that improve, refute or complement them.

Finally, this study cannot assess if practitioners, such as policy-makers or company managers, share the foundations embedded in the academic arena. We thus welcome researchers to conduct validity tests of the foundations revealed in this work and verify and complement them in contexts outside of the academic literature.

Acknowledgement

The authors would like to thank the Gates Cambridge Trust, who provided funding for this research.

References

Abernathy, W., Utterback, J., 1978. Patterns of industrial innovation. Technol. Rev. 41–47.
Abramovitz, M., 1986. Catching up, forging ahead, and falling behind. J. Econ. Hist. 46, 385–406.
Alvesson, M., Sandberg, J., 2011. Generating research questions through problematization. Acad. Manag. Rev. 38, 247–271. https://doi.org/10.5465/AMR.2011.59330882.
Amsden, A., 2002. The Rise of "The Rest": Challenges to the West from Late-industrializing Economies. Oxford University Press. https://doi.org/10.2307/3089111.
Arthur, W.B., 1989. Competing technologies, increasing returns, and lock-in by historical events. Econ. J. 99, 116–131.
Barras, R., 1986. Towards a theory of innovation in services. Res. Pol. 15, 161–173. https://doi.org/10.1016/0048-7333(86)90012-0.
Basu, R., Banerjee, P., Sweeny, E., 2013. Frugal innovation: core competencies to address global sustainability. J. Manag. Glob. Sustain. 1, 63–82. https://doi.org/10.13185/JM2013.01204.
Beck, U., 1999. World Risk Society. Polity Press, Cambridge.
Bellis, N. De, 2009. Bibliometrics and Citation Analysis. The Scarecrow Press.
Berkhout, F., Stirling, A., Smith, A., 2004. Socio-technological regimes and transition contexts. Syst. Innov. Transit. Sustain. Theor. Evid. Pol. 44, 48–75. https://doi.org/10.4337/9781845423421.00013.
Bijker, W., 1995. Of Bicycles, Bakelites, and Bulbs: toward a Theory of Sociotechnical Change. The MIT Press, Cambridge, Massachussets. https://doi.org/10.2307/2077312.
Blizzard, J.L., Klotz, L.E., 2012. A framework for sustainable whole systems design. Des. Stud. 33, 456–479. https://doi.org/10.1016/j.destud.2012.03.001.
Borrás, S., Edler, J., 2015. The Governance of Socio-technical Systems: Explaining Change.
Brundtland, G.H., 1987. Our common future: report of the world commission on environment and development. Med. Confl. Surviv. 4, 300. https://doi.org/10.1080/07488008808408783.
Cabrera, D., 2006. Systems Thinking. PhD Thesis. Cornell University.
Capra, F., 1983. The Turning Point : Science, Society, and the Rising Culture. Bantam Books.
Carlsson, B., Jacobsson, S., Holmén, M., Rickne, A., 2002. Innovation systems:

analytical and methodological issues. Res. Pol. 31, 233–245. https://doi.org/10.1016/S0048-7333(01)00138-X.
Ceschin, F., Gaziulusoy, I., 2016. Evolution of design for sustainability: from product design to design for system innovations and transitions. Des. Stud. 47, 118–163. https://doi.org/10.1016/j.destud.2016.09.002.
Chang, H.-J., 2002. Kicking Away the Ladder: Development Strategy in Historical Perspective. Anthem.
Charnley, F., Lemon, M., Evans, S., 2011. Exploring the process of whole system design. Des. Stud. 32, 156–179. https://doi.org/10.1016/j.destud.2010.08.002.
Chesbrough, H., 2010. Business model innovation: opportunities and barriers. Long. Range Plan. 43, 354–363. https://doi.org/10.1016/j.lrp.2009.07.010.
Chesbrough, H.W., 2003. Open Innovation ;: the New Imperative for Creating and Profiting from Technology. Harvard Business School Press.
Clark, K., Fujimoto, T., 1991. Product Development Performance : Strategy, Organization, and Management in the World Auto Industry. Harvard Business School Press.
Clark, W., Crutzen, P., 2005. Science for Global Sustainability: Toward a New Paradigm. KSG Work. Pap. No. 1–28.
Coenen, L., Benneworth, P., Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. Res. Pol. 41, 968–979. https://doi.org/10.1016/j.respol.2012.02.014.
Cohen, M.J., 2006. Ecological modernization and its discontents: the American environmental movement's resistance to an innovation-driven future. Futures 38, 528–547. https://doi.org/10.1016/j.futures.2005.09.002.
Cohen, M.J., 1997. Risk society and ecological modernisation alternative visions for post-industrial nations. Futures 29, 105–119. https://doi.org/10.1016/S0016-3287(96)00071-7.
Cooke, P., Gomez Uranga, M., Etxebarria, G., 1997. Regional innovation systems: institutional and organisational dimensions. Res. Pol. 26, 475–491. https://doi.org/10.1016/S0048-7333(97)00025-5.
Crane, A., Pallazzo, G., Spence, L.J., Matten, D., 2014. Contesting the value "creating shared value" concept. Calif. Manag. Rev. 56, 130–154. https://doi.org/10.1525/cmr.2014.56.2.130.
Daly, H.E., 1991. Steady-state Economics. Island Press.
Daly, H.E., Townsend, K.N., Kenneth, N., 1993. Valuing the Earth: Economics, Ecology, Ethics. MIT Press.
De Haan, F.J., Ferguson, B.C., Adamowicz, R.C., Johnstone, P., Brown, R.R., Wong, T.H.F., 2014. The needs of society: a new understanding of transitions, sustainability and liveability. Technol. Forecast. Soc. Change 85, 121–132. https://doi.org/10.1016/j.techfore.2013.09.005.
De Jouvenel, H., 2000. A brief methodological guide to scenario building. Technol. Forecast. Soc. Change 65, 37–48.
Doloreux, D., Parto, S., 2005. Regional innovation systems: current discourse and unresolved issues. Technol. Soc. 27, 133–153. https://doi.org/10.1016/j.techsoc.2005.01.002.
Dosi, G., 1982. Technological paradigms and technological trajectories. A suggested interpretation of the determinants and directions of technical change. Res. Pol. 11, 147–162. https://doi.org/10.1016/0048-7333(82)90016-6.
Dosi, G., Nelson, R.R., Winter, S.G., 2000. The Nature and Dynamics of Organizational Capabilities. Oxford University Press.
Dreborg, K.H., 1996. Essence of backcasting. Futures 28, 813–828. https://doi.org/10.1016/S0016-3287(96)00044-4.
Durance, P., Godet, M., 2010. Scenario building: uses and abuses. Technol. Forecast. Soc. Change 77, 1488–1492.
Easterby-Smith, M., Thorpe, R., Jackson, P., 2015. Management and Business Research, fifth ed. Sage, London.
Eisenhardt, K.M., Tabrizi, B.N., 1995. Accelerating adaptive processes: product innovation in the global computer industry. Adm. Sci. Q. 40, 84–110. https://doi.org/10.2307/2393701.
Ekins, P., 2011. System innovation for environmental sustainability: concepts, policies and political economy. In: International Economics of Resource Efficiency. Physica-Verlag HD, Heidelberg, pp. 51–88. https://doi.org/10.1007/978-3-7908-2601-2_3.
Elkington, J., 1999. Cannibals with Forks : the Triple Bottom Line of 21st Century Business. Capstone.
Elzen, B., Geels, F.W., Green, K., 2004. System Innovation and the Transition to Sustainability : Theory, Evidence and Policy. Edward Elgar.
Esty, D.C., Winston, A.S., 2009. Green to Gold : How Smart Companies Use Environmental Strategy to Innovate, Create Value, and Build Competitive Advantage. Wiley.
Ettlie, J.E., Reza, E.M., 1992. Organizational integration and process innovation. Acad. Manag. J. 35, 795–827. https://doi.org/10.2307/256316.
Evans, S., Bergendahl, M., Gregory, M., Ryan, C., 2009. Towards a sustainable industrial system. In: Int. Manuf. Profr. Symp. Cambridge UK, pp. 1–25, 978-1-902546-80-3.
Ezrahi, Y., 1990. The Descent of Icarus: Science and the Transformation of Contemporary Democracy. Harvard University Press.
Fagerberg, J., 1994. Technology and international differences in growth rates. J. Econ. Lit. 32, 1147–1175. https://doi.org/10.2307/2728605.
Farla, J., Markard, J., Raven, R., Coenen, L., 2012. Sustainability transitions in the making: a closer look at actors, strategies and resources. Technol. Forecast. Soc. Change 79, 991–998. https://doi.org/10.1016/j.techfore.2012.02.001.
Forrester, J.W., 1961. Industrial Dynamics, Reprinted. Martino Publ.
Fowke, R., Prasad, D., 1996. Sustainable development, cities and local government. Aust. Plan. 33, 61–66. https://doi.org/10.1080/07293682.1996.9657714.
Freeman, C., 1995. The ' National System of Innovation ' in Historical Perspective, pp. 5–24.
Freeman, C., 1991. Innovation, changes of techno-economic paradigm and biological analogies in economics. Rev.. économique 42, 211. https://doi.org/10.2307/3502005.
Freeman, C., Louçã, F., 2001. As Time Goes By: from the Industrial Revolutions to the Information Revolution. Oxford University Press.
Freeman, C., Perez, C., 1988. Structural crises of adjustment, business cycles and investment behaviour. In: Dosi, G., et al. (Eds.), Technical Change and Economic Theory, pp. 38–66. https://doi.org/10.2307/2234048.
Freeman, C., Soete, L., 2000. The Economics of Industrial Innovation.
Funtowicz, S.O., Ravetz, J.R., 1995. Science for the post normal age. In: Westra, L., Lemons, J. (Eds.), Perspectives on Ecological Integrity. Springer Netherlands, Dordrecht, pp. 146–161. https://doi.org/10.1007/978-94-011-0451-7_10.
Funtowicz, S.O., Ravetz, J.R., 1990. Uncertainty and Quality in Science for Policy 1992. https://doi.org/10.1007/978-94-009-0621-1.
Furman, J.L., Porter, M.E., Stern, S., 2002. The determinants of national innovative capacity. 2Research Policy 31, 899–933. https://doi.org/10.5465/APBPP.2000.5536001.
Gallouj, F., Weinstein, O., 1997. Innovation in services. Elsevier Res. Pol. 26, 537–556. https://doi.org/10.1016/S0048-7333(97)00030-9.
Gaziulusoy, A.I., Brezet, H., 2015. Design for system innovations and transitions: a conceptual framework integrating insights from sustainability science and theories of system innovations and transitions. J. Clean. Prod. 108, 1–11. https://doi.org/10.1016/j.jclepro.2015.06.066.
Geels, F.W., 2010. Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res. Pol. 39, 495–510. https://doi.org/10.1016/j.respol.2010.01.022.
Geels, F.W., 2005. The dynamics of transitions in socio-technical systems: a multi-level analysis of the transition pathway from horse-drawn carriages to automobiles (1860–1930). Technol. Anal. Strat. Manag. 17, 445–476. https://doi.org/10.1080/09537320500357319.
Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Res. Pol. 33, 897–920. https://doi.org/10.1016/j.respol.2004.01.015.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Pol. 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Pol. 36, 399–417. https://doi.org/10.1016/j.respol.2007.01.003.
Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy – a new sustainability paradigm? J. Clean. Prod. 143, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048.
George, G., Mcgahan, A.M., Prabhu, J., 2012. Innovation for inclusive growth: towards a theoretical framework and a research agenda. J. Manag. Stud. 49, 661–683. https://doi.org/10.1111/j.1467-6486.2012.01048.x.
Gerschenkron, A., 1962. Economic Backwardness in Historical Perspective: a Book of Essays. Harvard University Press.
Goffin, K., Mitchell, R., 2010. Innovation Management : Strategy and Implementation Using the Pentathlon Framework. Palgrave Macmillan.
Graddy-Reed, A., Feldman, M.P., 2015. Stepping up: an empirical analysis of the role of social innovation in response to an economic recession. Camb. J. Reg. Econ. Soc. 8, 293–312. https://doi.org/10.1093/cjres/rsv008.
Grant, B.M., Giddings, L.S., 2002. Making sense of methodologies: a paradigm framework for the novice researcher. Contemp. Nurse J. Aust. Nurse Prof. 13, 10–28. https://doi.org/10.5172/conu.13.1.10.
Gregory, M.J., 1995. Technology management: a process approach. J. Eng. Manuf. 209, 347–356. https://doi.org/10.1243/PIME_PROC_1995_209_094_02.
Grey, W., 1993. Anthropocentrism and deep ecology. Australas. J. Philos. 71, 463–475. https://doi.org/10.1080/00048409312345442.
Hamilton, C., 2004. The Growth Fetish. Pluto Press.
Hardin, G., 1968. The tragedy of the commons. Science (80-.) 162, 1243–1248. https://doi.org/10.1126/science.162.3859.1243.
Hart, S.L., 2000. Beyond greening: strategies for a sustainable world. Harv. Bus. Rev. 97015.
Hart, S.L., Milstein, M.B., 2003. Creating sustainable value. Acad. Manag. Exec. 17, 56–67. https://doi.org/10.5465/AME.2003.10025194.
Hipp, C., Grupp, H., 2005. Innovation in the service sector: the demand for service-specific innovation measurement concepts and typologies. Res. Pol. 34, 517–535. https://doi.org/10.1016/j.respol.2005.03.002.
Hodgson, G., 2005. Institutions and economic development: constraining, enabling and reconstituting. In: Dymski, G., De Paula, S. (Eds.), Reimagining Growth: towards a Renewal of Development Theory. Zed Books, pp. 88–95.
Holmberg, J., Robert, K.-H., 2000. Backcasting — a framework for strategic planning. Int. J. Sustain. Dev. World Ecol. 7, 291–308. https://doi.org/10.1080/13504500009470049.
Jackson, T., 2009. Prosperity without Growth? the Transition to a Sustainable Economy. https://doi.org/10.1016/j.jclepro.2009.07.001.
Jänicke, M., Jacob, K., 2006. Environmental Governance in Global Perspective: New Approaches to Ecological Modernisation (Berlin).
Jasanoff, S., 2010. A new climate for society. Theor. Cult. Soc. 27, 233–253. https://doi.org/10.1177/0263276409361497.
Jasanoff, S., 2009. Governing Innovation [WWW Document]. Semin, p. 507.
Jordan, A., Lenschow, A., 2008. Innovation in Environmental Policy?: Integrating the Environment for Sustainability. Edward Elgar.

Jørgensen, U., 2012. Mapping and navigating transitions - the multi-level perspective compared with arenas of development. Res. Pol. 41, 996–1010. https://doi.org/10.1016/j.respol.2012.03.001.
Kallis, G., 2011. In defence of degrowth. Ecol. Econ. 70, 873–880. https://doi.org/10.1016/j.ecolecon.2010.12.007.
Kates, R.W., Parris, T.M., 2003. Long-term trends and a sustainability transition. Proc. Natl. Acad. Sci. U. S. A 100, 8062–8067. https://doi.org/10.1073/pnas.1231331100.
Kates, R.W., Parris, T.M., Leiserowitz, A.A., 2005. What is sustainable development? Goals, indicators, values, and practice. Environ. Sci. Pol. 47, 8–21. https://doi.org/10.1080/00139157.2005.10524444.
Kauffman, S.A., 1995. At Home in the Universe : the Search for Laws of Self-organization and Complexity. Oxford University Press.
Kemp, R., 1994. Technology and the transition to environmental sustainability. Futures 26, 1023–1046. https://doi.org/10.1016/0016-3287(94)90071-X.
Kemp, R., Pearson, P., 2007. Final Report MEI Project about Measuring Eco-innovation. Final report MEI project about measuring ecoinnovation.
Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strat. Manag. 10, 175–195. https://doi.org/10.1080/09537329808524310.
Kharrazi, A., Fath, B., Katzmair, H., 2016. Advancing empirical approaches to the concept of resilience: a critical examination of panarchy, ecological information, and statistical evidence. Sustainability 8, 935. https://doi.org/10.3390/su8090935.
Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Pol. 45, 205–217. https://doi.org/10.1016/j.respol.2015.09.008.
Knutas, A., Hajikhani, A., Salminen, J., Ikonen, J., Porras, J., 2015. Cloud-based bibliometric analysis service for systematic mapping studies. ACM Int. Conf. Proceeding Ser 1008, 184–191. https://doi.org/10.1145/2812428.2812442.
Kuhn, T.S., 1996. The Structure of Scientific Revolutions. University of Chicago Press.
Lafferty, W., Hovden, E., 2002. Environmental Policy Integration: towards an Analytical Framework?, Report No. 7/02. https://doi.org/10.1126/science.ns-20.502.157.
Lanahan, L., Feldman, M.P., 2015. Multilevel innovation policy mix: a closer look at state policies that augment the federal SBIR program. Res. Pol. 44, 1387–1402. https://doi.org/10.1016/j.respol.2015.04.002.
Latour, B., Woolgar, S., 1986. Laboratory Life: the Construction of Scientific Facts. Princeton University Press, New Jersey, 08540.
Leach, M., Scoones, I., Stirling, A., 2007. Pathways to Sustainability: an Overview of the STEPS Centre Approach 19.
Leach, M., Scoones, I., Wynne, B., 2005. Science, Citizenship and Globalization. Zed Press.
Leonard-Barton, D., 1992. The factory as the learning laboratory. Sloan Manag. Rev. 34, 23–28.
Leydesdorff, L., 2000. The triple helix: an evolutionary model of innovations. Res. Pol. 29, 243–255. https://doi.org/10.1016/S0048-7333(99)00063-3.
Loorbach, D., 2010. Transition management for sustainable development: a prescriptive, complexity-based governance framework. Governance 23, 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x.
Lundvall, B.-Å., Johnson, B., Andersen, E.S., Dalum, B., 2002. National systems of production, innovation and competence building. Res. Pol. 31, 213–231. https://doi.org/10.1016/S0048-7333(01)00137-8.
Lundvall, B.-A., Joseph, K., Chaminade, C., Vang, J., 2009. Handbook of Innovation Systems and Developing Countries: Building Domestic Capabilities in a Global Setting. Edward Elgar.
MacKerron, G., Berkhout, F., 2009. Learning to listen: institutional change and legitimation in UK radioactive waste policy. J. Risk Res. 12, 37–41. https://doi.org/10.1080/13669870903126085.
Malerba, F., 2004. Sectoral Systems of Innovation : Concepts, Issues and Analyses of Six Major Sectors in Europe. Cambridge University Press.
Malerba, F., 2002. Sectoral systems of innovation and production. Res. Pol. 31, 247–264. https://doi.org/10.1016/S0048-7333(01)00139-1.
Markard, J., Raven, R., Truffer, B., 2012. Sustainability transitions: an emerging field of research and its prospects. Res. Pol. 41, 955–967. https://doi.org/10.1016/j.respol.2012.02.013.
Martin, B.R., 2012. The evolution of science policy and innovation studies. Res. Pol. 41, 1219–1239. https://doi.org/10.1016/j.respol.2012.03.012.
Martin, B.R., Nightingale, P., Yegros-Yegros, A., 2012. Science and technology studies: exploring the knowledge base. Res. Pol. 41, 1182–1204. https://doi.org/10.1016/j.respol.2012.03.010.
Mazzucato, M., 2013. The Entrepreneurial State: Debunking Public Vs. Private Sector Myths. Anthem Press.
McDowall, W., 2012. Technology roadmaps for transition management: the case of hydrogen energy. Technol. Forecast. Soc. Change 79, 530–542. https://doi.org/10.1016/j.techfore.2011.10.002.
Mckelvey, B., 2002. Managing Coevolutionary Dynamics. 8th EGOS Colloq.
Mcwilliams, A., 2016. Corporate Social Responsibility : a Theory of the Firm Perspective Author (S): Abagail McWilliams and Donald Siegel Source : the Academy of Management Review, vol. 26. Academy of Management Stable, pp. 117–127. No. 1 (Jan., 2001).
Meadows, D., 2008. Thinking in Systems: a Primer, Sustainability INstitute. https://doi.org/10.1017/CBO9781107415324.004.
Meadows, D., 2002. Dancing with Systems, Systems Thinker.
Meadows, D., Meadows, D., Randers, J., Behrens, W., 1972. The Limits to Growth: a Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books, New York. https://doi.org/10.1111/j.1752-1688.1972.tb05230.x.
Meerow, S., Newell, J.P., 2015. Resilience and complexity: a bibliometric review and prospects for industrial ecology. J. Ind. Ecol. 19, 236–251. https://doi.org/10.1111/jiec.12252.
Meyer, M.H., Utterback, J.M., 1993. The product family and the dynamics of core capability. MIT Sloan Manag. Rev. 34, 29–47 (Article).
Middleton, N., O'Keefe, P., 1993. Tears of the Crocodile: from Rio to Reality in the Developing World. Pluto Press.
Miller, C.A., 2005. New civic epistemologies of quantification: making sense of indicators of local and global sustainability. Sci. Technol. Hum. Val. 30, 403–432. https://doi.org/10.1177/0162243904273448.
Millstone, E., 2007. Can food safety policy-making be both scientifically and democratically legitimated? If so, how? J. Agric. Environ. Ethics 20, 483–508. https://doi.org/10.1007/s10806-007-9045-x.
Mingers, J., White, L., 2009. A review of the recent contribution of systems thinking to operational research and management science q. Eur. J. Oper. Res. 207, 1147–1161. https://doi.org/10.1016/j.ejor.2009.12.019.
Mokyr, J., 1990. The Lever of Riches ;: Technological Creativity and Economic Progress. Oxford University Press.
Mortara, L., Minshall, T., 2011. How do large multinational companies implement open innovation? Technovation 31, 586–597. https://doi.org/10.1016/j.technovation.2011.05.002.
Morton, T., 2007. Ecology without Nature ;: Rethinking Environmental Aesthetics. Harvard University Press.
Nakata, C., Weidner, K., 2012. Enhancing new product adoption at the base of the pyramid: a contextualized model. J. Prod. Innovat. Manag. 29, 21–32. https://doi.org/10.1111/j.1540-5885.2011.00876.x.
National Research Council, 1999. Our Common Journey. National Academies Press, Washington, D.C. https://doi.org/10.17226/9690.
Nelson, R.R., Winter, S.G., 1982. An Evolutionary Theory of Economic Change, Cambridge MA Belknap. https://doi.org/10.2307/2232409.
North, D., 1990. Institutions, Institutional Change and Economic Performance. Cambridge University Press.
O'Riordan, 1993. The politics of sustainability. In: Turner, K. (Ed.), Sustainable Environment Economics and Management: Principles and Practice. Belhaven Press, London, pp. 37–69.
OECD, 2011. Better Policies to Support Eco-innovation, OECD Studies on Environmental Innovation. OECD Publishing. https://doi.org/10.1787/9789264096684-en.
Penna, C.C.R., Geels, F.W., 2012. Multi-dimensional struggles in the greening of industry: a dialectic issue lifecycle model and case study. Technol. Forecast. Soc. Change 79, 999–1020. https://doi.org/10.1016/j.techfore.2011.09.006.
Penrose, E., 2013. The Theory of the Growth of the Firm. Martino Fine Books.
Perez, C., 2002. Technological Revolutions and Financial Capital : the Dynamics of Bubbles and Golden Ages. E. Elgar Pub.
Pestre, D., 2008. Challenges for the democratic management of technoscience: governance, participation and the political today. Sci. Cult. (Lond) 17, 101–119. https://doi.org/10.1080/09505430802062869.
Phaal, R., Farrukh, C.J.P., Probert, D.R., 2001. A framework for supporting the management of technological innovation. Eng. Dep. Univ. 1–14. https://doi.org/10.1504/Ijtm.2004.003878. Cambridge.
Pincetl, S., Chester, M., Circella, G., Fraser, A., Mini, C., Murphy, S., Reyna, J., Sivaraman, D., 2014. Enabling Future Sustainability Transitions: an Urban Metabolism Approach to Los Angeles Pincetl et al. Enabling Future Sustainability Transitions. J. Ind. Ecol. 18, 871–882. https://doi.org/10.1111/jiec.12144.
Pisano, G.P., Verganti, R., 2008. Which kind of collaboration is right for you? Harv. Bus. Rev. 86, 1–7 (Article).
Pittaway, L., Robertson, M., Munir, K., Denyer, D., Neely, A., 2004. Networking and Innovation in the UK: a Systematic Review of the Literature. Advanced Institute of Management Research.
Porter, M.E., Kramer, M.R., 2011. Creating shared value. Harv. Bus. Rev. 63–77. https://doi.org/10.1108/09600039410055963.
Prahalad, C.K., 2004. The Fortune at the Bottom of the Pyramid: Eradicating Poverty through Profits: C.K. Prahalad: 9780131467507: Amazon.Com: Books. Wharton School Publishing.
Prahalad, C.K., Di Benedetto, A., Nakata, C., 2012. Bottom of the pyramid as a source of breakthrough innovations. J. Prod. Innovat. Manag. 29, 6–12. https://doi.org/10.1111/j.1540-5885.2011.00874.x.
Prahalad, C.K., Hart, S.L., 2002. The fortune at the bottom of the pyramid. Strateg. Mag 273. https://doi.org/10.2139/ssrn.914518.
Radjou, N., Prabhu, J., Ahuja, S., 2012. Jugaad Innovation: Think Frugal, Be Flexible, Generate Breakthrough Growth. John Wiley & Sons.
Rip, A., 2006. Reflexive governance for sustainable development. In: Voss, J.-P., Bauknecht, D., Kemp, R. (Eds.), Reflexive Governance for Sustainable Development. Edward Elgar, pp. 82–100.
Rip, A., Schot, J., 1996. The past and future of constructive technology assessment. Technol. Forecast. Soc. Change 54, 251–268.
Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H., Nykvist, B., De Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falke, M., J F, 2009. Planetary Boundaries: exploring the safe operating space for humanity. Ecol. Soc. 14 https://doi.org/10.1007/s13398-014-0173-7.2.

Rotmans, J., Kemp, R., van Asselt, M., 2001. More evolution than revolution: transition management in public policy. foresight 3, 15–31. https://doi.org/10.1108/14636680110803003.
Roussel, P. a, Saad, K.N., Erickson, T.J., 1991. Third-generation R&D Management 6.
Sachs, J., 2015. The Age of Sustainable Development., the Age of Sustainable Development. Columbia University Press. https://doi.org/10.1080/01944363.2015.1077080.
Savaget, P., Acero, L., 2017. Plurality in understandings of innovation, sociotechnical progress and sustainable development: an analysis of OECD expert narratives. Publ. Understand. Sci. https://doi.org/10.1177/0963662517695056, 096366251769505.
Schiederig, T., Tietze, F., Herstatt, C., 2012. Green innovation in technology and innovation management – an exploratory literature review. R D Manag. 42, 180–192. https://doi.org/10.1111/j.1467-9310.2011.00672.x.
Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Technol. Anal. Strat. Manag. 20, 537–554. https://doi.org/10.1080/09537320802292651.
Seiffert, M., Loch, C., 2005. Systemic thinking in environmental management: support for sustainable development. J. Clean. Prod. 13, 1197–1202. https://doi.org/10.1016/j.jclepro.2004.07.004.
Senge, P.M., 1990. The Fifth Discipline: the Art and Practice of the Learning Organization. Reprinted. ed. Doubleday/Currency.
Seyfang, G., Smith, A., 2007. Grassroots innovations for sustainable development: towards a new research and policy agenda. Environ. Polit. 16, 584–603. https://doi.org/10.1080/09644010701419121.
Shaw, A., Burch, S., Kristensen, F., Robinson, J., Dale, A., 2014. Accelerating the sustainability transition: exploring synergies between adaptation and mitigation in British Columbian communities. Global Environ. Change 25, 41–51. https://doi.org/10.1016/j.gloenvcha.2014.01.002.
Shove, E., Walker, G., 2010. Governing transitions in the sustainability of everyday life. Res. Pol. 39, 471–476. https://doi.org/10.1016/j.respol.2010.01.019.
Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Pol. 41, 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012.
Smith, A., Stirling, A., 2007. Moving outside or inside? Objectification and reflexivity in the governance of socio-technical systems. J. Environ. Pol. Plann. 9, 351–373. https://doi.org/10.1080/15239080701622873.
Smith, A., Stirling, A., Berkhout, F., 2005. The governance of sustainable socio-technical transitions. Res. Pol. 34, 1491–1510. https://doi.org/10.1016/j.respol.2005.07.005.
Smith, A., Voss, J.P., Grin, J., 2010. Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Res. Pol. 39, 435–448. https://doi.org/10.1016/j.respol.2010.01.023.
Stegmaier, P., Kuhlmann, S., Visser, V., 2014. The discontinuation of socio-technical systems as a governance problem. Gov. Socio-technical Syst. Explain. Chang 111–131. https://doi.org/10.4337/9781784710194.00015.
Stirling, A., 2014. From sustainability, through diversity to transformation: towards more reflexive governance of vulnerability. In: Hommels, A., Mesman, J., W B (Eds.), Vulnerability in Technological Cultures: New Directions in Research and Governance. MIT Press, Cambridge, Massachussets.
Stirling, A., 2009. Direction, distribution and diversity! Pluralising progress in innovation, sustainability and development. STEPS Work. Pap 32, 1–45.
Stirling, A., 2007. Deliberate futures: precaution and progress in social choice of sustainable technology. Sustain. Dev. 15, 286–295. https://doi.org/10.1002/sd.347.
Stirling, A., 2003. Risk, uncertainty and precaution: some instrumental implications from the social sciences. In: Berkhout, F., Leach, M., Scoones, I. (Eds.), Negotiating Change: New Perspectives from the Social Sciences. Edward Elgar, pp. 33–76. https://doi.org/10.4337/9781843765653.00008.
STRN, 2010. A Mission Statement and Research Agenda for the Sustainability Transitions Research Network.
Sushandoyo, D., Magnusson, T., 2014. Strategic niche management from a business perspective: taking cleaner vehicle technologies from prototype to series production. J. Clean. Prod. 74, 17–26. https://doi.org/10.1016/j.jclepro.2014.02.059.
Teece, D.J., Pisano, G., Shuen, A., 2008. Dynamic capabilties and strategic management. Strat. Manag. J. 18, 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7<509::AID-SMJ882>3.0.CO;2-Z.
Teisman, G.R., van Buuren, A., Gerrits, L., 2010. Managing Complex Governance Systems. Routledge.
Thompson, M., Warburton, M., Hatley, T., 2007. Uncertainty on a Himalayan scale : an institutional theory of environmental perception and a strategic framework for the sustainable development of the Himalaya. Himal B. Class. Ser 152. https://doi.org/10.2307/2803394.
Tidd, J., 2001. Innovation management in context: environment, organization and performance. Int. J. Manag. Rev. 3, 169–183. https://doi.org/10.1111/1468-2370.00062.
Tranfield, D., Denyer, D., Smart, P., 2003. Towards a methodology for developing evidence-informed management knowledge by means of systematic review *. Br. J. Manag. 14, 207–222. https://doi.org/10.1111/1467-8551.00375.
Turner, B.L., Kasperson, R., Matson, P., McCarthy, J., Corell, R., Christensen, L., Eckley, N., Kasperson, J., Luers, A., Martello, M., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. Proc. Natl. Acad. Sci. Unit. States Am. 100, 8074–8079. https://doi.org/10.1073/pnas.1231335100.
Turnheim, B., Berkhout, F., Geels, F., Hof, A., McMeekin, A., Nykvist, B., van Vuuren, D., 2015. Evaluating sustainability transitions pathways: bridging analytical approaches to address governance challenges. Global Environ. Change 35, 239–253. https://doi.org/10.1016/j.gloenvcha.2015.08.010.
UNCED, 1992. AGENDA 21. Rio de Janeiro.
United Nations, 2015. Global Sustainable Development Report.
Utterback, J.M., Abernathy, W.J., 1975. A dynamic model of process and product innovation. Omega 3, 639–656. https://doi.org/10.1016/0305-0483(75)90068-7.
Van de Poel, I., 2000. On the role of outsiders in technical development. Technol. Anal. Strat. Manag. 12, 383–397. https://doi.org/10.1080/09537320050130615.
Van de Ven, A., Polley, D., Garud, R., Venkataraman, S., 1999. The Innovation Journey. Oxford University Press.
Viotti, E.B., 2002. National learning systems: a new approach on technological change in late industrializing economies and evidences from the cases of Brazil and South Korea. Technol. Forecast. Soc. Change 69, 653–680. https://doi.org/10.1016/S0040-1625(01)00167-6.
Von Hippel, E., 2001. Perspective: user toolkits for innovation. J. Prod. Innovat. Manag. 18, 247–257. https://doi.org/10.1016/S0737-6782(01)00090-X.
Von tunzelmann, N., Malerba, F., Nightingale, P., Metcalfe, S., 2008. Technological paradigms: past, present and future. Ind. Corp. Change 17, 467–484. https://doi.org/10.1093/icc/dtn012.
Voß, J.P., Smith, A., Grin, J., 2009. Designing long-term policy: rethinking transition management. Pol. Sci. 42, 275–302. https://doi.org/10.1007/s11077-009-9103-5.
Weber, R., 1990. Basic Content Analysis. SAGE Publications.
Webster, J., Watson, R.T., 2002. Analyzing the past to prepare for the Future : writing a literature review. MIS Q. 26 xiii–xxiii.
Webster, K., 2015. The Circular Economy: a Wealth of Flows. Ellen MacArthur Foundation, Isle of Wight.
Whetten, D., 1989. What constitutes a theoretical contribution? Acad. Manag. Rev. 14, 490–495.
White, L., 1967. The historical roots of our ecologic crisis. Science 155, 1203–1207. https://doi.org/10.1126/science.155.3767.1203.
Williams, C.C., Millington, A.C., 2004. The diverse and contested meanings of sustainable development. Geogr. J. 170, 99–104. https://doi.org/10.1111/j.0016-7398.2004.00111.x.
Wittmayer, J.M., Schäpke, N., 2014. Action, research and participation: roles of researchers in sustainability transitions. Sustain. Sci. 9, 483–496. https://doi.org/10.1007/s11625-014-0258-4.
Wohlin, C., 2014. Guidelines for snowballing in systematic literature studies and a replication in software engineering. In: EASE'14 Proc. 18th Int. Conf. Eval. Assess. Softw. Eng.
Wynne, B., 1992. Uncertainty and environmental learning - reconceiving science and policy in the preventive paradigm. Glob. Environ. Chang. Policy Dimens 2, 111–127.
Zott, C., Amit, R., Massa, L., 2011. The business model: recent developments and future research. J. Manag. 37, 1019–1042. https://doi.org/10.1177/0149206311406265.