Capabilities, Networks, and Directionality

Innovation Policy for Sustainable Development Goals

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A thesis submitted to Imperial College London
for the Degree of Doctor of Philosophy

Centre for Environmental Policy, Faculty of Natural Sciences

May 2019

Declaration of originality

I declare that the thesis has been composed by myself and that the work has not been submitted for any other degree or professional qualification. I confirm that the work submitted is my own, except where work which has formed part of jointly-authored publications has been included. My contribution and those of the other authors to this work have been explicitly indicated below. I confirm that appropriate credit has been given within this thesis where reference has been made to the work of others.

The conceptual framework presented in section 1.1 was previously published in Research Policy, 2019, Volume 48, Issue 4 as 'Transformative innovation policy: Addressing variety in an emerging policy paradigm' by Gijs Diercks, Henrik Larsen (author), and Fred Steward (first supervisor). This study was conceived by all of the authors.

The work presented in chapter 4 is currently under review in a scientific journal. The manuscript was submitted by Henrik Larsen (author), Ulrich E. Hansen (second supervisor) and Paulo N. Figueiredo. The main idea of the paper was conceived by all the authors. As the main author, I conducted the fieldwork, data analysis, and paper writing. The co-authors contributed during the process by providing feedback and ideas.

Copyright declaration

Acknowledgements

During the writing of this thesis, I have received a great deal of support and encouragement. First, I would like to express my gratitude and appreciation to my supervisor Professor Fred Steward for his invaluable guidance, patience, and continuous support throughout the research process. Second, I would like to thank my second supervisor Doctor Ulrich E. Hansen for all his advice and for hosting me as a visiting PhD student at the UNEP DTU Partnership. I also wish to thank Professor Paulo N. Figueiredo, who generously shared his knowledge and experience while I was on fieldwork in Brazil. I am also grateful to Doctor Gijs Diercks for our valuable discussions on transformative innovation policy. I also wish to thank the rest of my supervisory committee at Imperial College London, including Professor Jim Skea, Professor Peter Pearson, and Doctor Keith Smith. They all are gratefully acknowledged. Third, I would like to thank all the interviewees, who generously gave their time to share their views, opinions, and experience. I also thank the R&D group leader and the R&D manager at Novozymes in Brazil for providing research access and for their helpful comments and feedback. I would also like to gratefully acknowledge the financial support provided by Climate-KIC in carrying out this research. Climate-KIC is supported by the European Institute of Innovation and Technology (EIT), a body of the European Union. I also wish to express my thanks to the staff of the Centre for Environmental Policy for their help and support. In the end, I am grateful to my father and sister for their love and constant support throughout my studies and to my mother, who never saw this work finished. This work is dedicated to you. I am also very much grateful to the rest of my family, friends, and colleagues, who have supported me along the way. Above all, I wish to thank my wife, Camila, for all her love, patience, and endless support.

Abstract

Innovation is at the heart of policy discussions on how to achieve transformative change for sustainable development. Over the past decades, the systems of innovation approach has gained widespread use and is arguably the most influential framework guiding innovation scholars and policymakers today. Notwithstanding its explanatory power, the systems of innovation approach is mainly directed at optimising innovation systems to fulfil national economic policy objectives, such as growth, jobs, and competitiveness. The frame of reference has changed following the adoption of the United Nations 2030 Agenda for Sustainable Development and with it, the requirements for conceptual approaches that underpin innovation policy. It is increasingly understood that addressing societal challenges, such as poverty, inequality, and climate change, requires more than optimising innovation systems to fulfil economic policy objectives but also inducing directionality and processes of transformative change toward a broader range of societal and environmental objectives. This 'normative' turn towards transformative innovation policy is grounded in an understanding of system innovation of socio-technical systems towards more sustainable modes of production and consumption. The objective of this research is to conceptually refine the systems of innovation approach, and in particular revise the national innovation systems concept, thereby taking steps towards the development of a more integrative innovation policy framework that incorporates directionality and a strategic orientation of innovation systems to address contemporary societal challenges of the type of the United Nations Sustainable Development Goals. Focussing mainly on the needs and challenges of developing countries to accumulate the capabilities needed to manage innovation and technological change, three separate case studies are used to validate central features of transformative innovation policy: *capabilities, networks, and directionality*. The first empirical chapter develops an understanding of how a Brazilian latecomer firm accumulated the capabilities needed to pursue innovation in new and different directions along more sustainable development pathways. The second empirical chapter furthers the understanding of how the formation of global innovation networks enhances interactive learning in national innovation systems, and in what way international technology cooperation complements creation and accumulation of innovation capabilities. A mapping of the growing number and variety of international cooperative initiatives in the context of climate change helps to illustrate the different forms of global innovation networks. The third empirical chapter integrates insights from the system innovation perspective and opens up the systems of innovation approach to incorporate directionality and a strategic orientation of innovation systems towards a broader range of societal and environmental objectives. The compatibility of the innovation policy framework is assessed with reference to the Sustainable Development Goals.

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1. Introduction

Burgeoning scientific evidence suggests that we have entered the era of the Anthropocene; a period of unprecedented human activity, causing a detrimental force of global environmental change (Rockström *et al.* 2009). It is widely acknowledged that continued unrestrained economic growth and resource consumption in a finite world transgress critical planetary boundaries and cause irreversible damage to fragile ecosystems (Steffen *et al.* 2015). It is increasingly understood that a fundamental transformation of society is needed to address the nature and complexity of accumulating environmental problems, such as climate change and natural resource scarcity (IPBES 2019). This coincides with the growing realisation that failure to provide an adequate policy response to these and other societal and environmental challenges impedes not only economic development but also threatens important progress made towards attaining vital sustainable development objectives (IPCC 2018). For instance, the rapidly increasing energy demand in developing countries is projected to more than double over the next decades and nearly one billion people still lack access to sustainable and modern forms of energy (IEA 2019).

To provide a comprehensive and robust policy response, in September 2015, world leaders came together at the historic United Nations (UN) Summit in New York City to agree on 17 Sustainable Development Goals (SDGs) and adopt the 2030 Agenda for Sustainable Development. Three months later, in December 2015, the Paris Agreement was adopted at the 21st Conference of the Parties to the United Nations Framework Convention on Climate Change. It is notable that the UN 2030 Agenda for Sustainable Development recognises innovation as indispensable for attaining the SDGs: 'the creation, development and diffusion of new innovations and technologies … are powerful drivers of economic growth and sustainable development' (2015:43). The innovation imperative in keeping the global temperature rise this century well below two degrees Celsius above pre-industrial levels is also reflected in article 10 of the Paris Agreement: 'accelerating, encouraging and enabling innovation is critical for an effective, long-term global response to climate change and promoting economic growth and sustainable development'.

At the same time, however, there is a growing awareness that conventional patterns of innovation are failing to address contemporary societal challenges and that alternative solutions should be pursued (Kern *et al.* 2014). It is increasingly recognised that current rationales for innovation policy are insufficient and new forms of challenge-led or mission-oriented approaches, breaking with prevalent practices and experiences are needed to address contemporary societal challenges that are deeply rooted in our current modes of production and consumption (e.g. Steward 2008, Weber and Rohracher 2012, Mazzucato 2017, Schot and Steinmueller 2018).

Despite internal differences, there is general agreement among this group of innovation scholars that to cope with the nature and complexity of contemporary societal and environmental challenges; there is a need for fundamental changes in the way societal functions are fulfilled.

Innovation scholars are therefore taking an increasing interest in exploring the directionality of innovation. There is an interest in not only the pace and scale of innovation but also in its direction and related normative questions (Schlaile *et al.* 2017). The academic debate about 'directional innovation' is not new and can be traced back, among others, to Stirling, where it is proposed that 'innovation is a vector, rather than just a scalar quantity. It includes the crucial but neglected normative property of direction' (2008:263). Acknowledging that innovation has not only a rate but also a direction opens the possibility that economic growth may be steered along more sustainable trajectories. For instance, as argued by Mazzucato, '… governments have the opportunity to determine the direction of growth by making strategic investments throughout the innovation chain and creating the potential for greater spillovers across multiple sectors …' (2018:806). Hence, in the context of this research, 'directionality' is understood as processes of transformative change that underpin significantly different directions of innovation along more sustainable development pathways, *thus opening up qualitatively different segments of the innovation frontier.*

The admission that innovation has a direction also implies that innovation can have negative outcomes and may contribute to exacerbate societal challenges, such as rising inequality, growing resource scarcity, and runaway climate change. As explained by Diercks *et al.,* 'it is an unavoidable observation that many of the societal challenges confronting the world today are caused by the direct effects or indirect consequences of previous innovations' (2019:883). Hence, rather than just assuming that all innovation is inherently 'good', innovation scholars have started to critically examine the interplay between economic growth and sustainable development and how this intricate relationship presents a dilemma on how to guide innovation towards desired societal objectives (e.g. Røpke 2012, Soete 2013, Dutrénit and Sutz 2014, Mazzucato and Perez 2014).

In this regard, there are significant collective action problems with current governance arrangements and little evidence to support that the prevailing neoliberal orthodoxy can ensure the necessary responses needed to decouple economic growth from environmental degradation (Hajer *et al.* 2015, Smith 2017, Hickel 2019). The long-standing often-undisputed pro-innovation discourse of ecological modernisation, industrial ecology approaches, and triple-bottom-line thinking arguably need to be complemented with a more heterogeneous set of 'disruptive' policy measures (Kemp *et al.* 2007, Turnheim and Geels 2012, Kivimaa and Kern 2016, Elkington 2018).[1]

[1] The political debate about the (in)compatibility between environmental sustainability and economic growth in a finite world is, of course, not new and goes back to, among others, Carson's 'Silent Spring' (1962), Ehrlich's 'Population Bomb' 1968), and influential reports such as 'Limits to Growth' (Meadows *et al.* 1972) and 'Our Common Future' (Brundtland 1987).

On this matter, the systems of innovation approach provides a powerful framework for innovation scholars and policymakers to identify the types of interacting components and relationships that are part of innovation systems in order to enhance their capacity to innovate (Carlsson *et al.* 2002). Nonetheless, the systems of innovation approach is mainly concerned with optimising innovation systems to enhance their capacity to innovate and fulfil economic policy objectives, such as growth, competitiveness, and jobs (Edquist 2006). It is increasingly understood that societal challenges of the type of the SDGs require more than optimising innovation systems to fulfil economic policy objectives but also inducing directionality and processes of transformative change toward a broader range of societal objectives (Weber and Rohracher 2012). In this sense, as explained by Schlaile *et al.*, 'directionality is not only about challenging the contemporary implicit focus on technological innovation and economic growth but also about opening up the IS [systems of innovation] approach for a variety of pathways' (2017:6). However, as described by Stirling, this notion of opening-up, 'the potential for pursuing a greater diversity of technological pathways', while strategically orienting innovation systems toward addressing societal challenges in many cases conflict with the conventional understanding of innovation as being collective, uncertain, and cumulative processes (2008:281).[2] Certainly, a key point to emerge from the literature is that innovation systems cannot be deliberately planned and controlled: 'even if we knew all the determinants of innovation processes in detail (which we certainly do not now, and perhaps never will), we would not be able to control them and design or 'build' SIs [innovation systems] on the basis of this knowledge' (Chaminade and Edquist 2010:101).

This thesis takes a different approach and departs from the understanding that innovation not only has a direction but also that it is possible to incorporate a strategic orientation of innovation systems towards desired societal and environmental objectives (see also Daimer *et al.* 2012, Weber and Rohracher 2012, Mazzucato 2019). At the same time, however, a central premise of this research is that the systems of innovation approach currently lacks the normative power expected from a framework with the ambition to address the contemporary societal challenges.

To clarify, this research is not questioning the contribution of research on innovation systems that has emerged over the last decades (see for instance Fagerberg *et al.* 2006, Smits *et al.* 2010). The detailed understanding of discrete determinants and dynamics that influence innovation has had important implications for the formulation and implementation of policy (Borrás and Edquist 2019). However, much research is preoccupied with optimising the interaction between the individual components of innovation systems to fulfil economic policy objectives (e.g. Chaminade

[2] See also Stirling (2009) for an in-depth discussion of the move from unitary to plural understandings of progress and how this multiplicity has profound implications for the governance of knowledge, innovation, and development.

and Edquist 2010, Lundvall 2016). A central proposition of this research is that the frame of reference has changed following the adoption of the UN 2030 Agenda for Sustainable Development and with it, the requirements for conceptual approaches that underpin innovation policy. Hence, to address contemporary societal challenges of the type of the SDGs, there is a need for new types of systemic policy instruments that allow for the systems of innovation approach to incorporate directionality and a strategic orientation of innovation systems.

To this end, innovation systems scholars have started to probe whether the systems of innovation approach can be revised to incorporate directional innovation and processes of transformative change (e.g. Daimer *et al.* 2012, Weber and Rohracher 2012, Lindner *et al.* 2016). Notwithstanding the growing research in the area, there is still a poor understanding of the possible refinements that are needed to open up the systems of innovation approach and go beyond the limitations of incremental and radical innovations in product, processes, and services towards implementing 'paradigm-breaking, system-wide novelty' (Steward 2008:15). To fill this knowledge gap, this research is concerned with conceptually refining the systems of innovation approach, thus taking steps towards the development of innovation policy framework that explicitly incorporate directionality and strategic orientation of innovation systems toward a broader range of societal and environmental objectives.

1.1 Transformative innovation policy: an emerging policy paradigm

A central argument of Diercks *et al.* and this research is that the aspiration for directional innovation to address societal and environmental challenges represents a turn towards *'transformative innovation policy'*, a new and emerging policy paradigm, which insists that 'innovation policy must not only optimise the innovation system to improve economic competitiveness and growth but also induce strategic directionality and guide processes of transformative change towards desired societal objectives' (2019:884). The policy paradigm for transformative change has emerged over the last decades and is receiving increasing attention, as reflected in recent publications and reports from the Organisation for Economic Co-operation and Development (OECD 2015) and the European Environmental Agency (EEA 2017).[3] Likewise, the call for directional innovation is reflected in mission-oriented policy agendas, such as the European Union growth strategy that seeks to tackle specific areas of societal concern (EC 2013) – see also the mission-oriented innovation policy proposal by Mazzucato to help frame the new European Union 2020 Horizon framework programme (EC 2018). Another example is the German Energiewende;

[3] See also the recent OECD Reviews of Innovation Policy of Sweden (2016), Norway (2017), and Finland (2018).

a comprehensive national programme that targets several sectors and technologies in the economy and enables bottom-up learning processes. With the strategic objectives to combat climate change, phase-out nuclear power, and improve energy security by substituting imported fossil fuel with renewable sources, Energiewende is providing a direction to innovation and economic growth across different sectors through targeted transformations in production, distribution, and consumption (see also Mazzucato 2018 for a discussion of previous mission-oriented agencies, such as the National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency (DARPA) set up with the ambition to meet specific societal objectives).

The intention here is not to elaborate in detail on the emerging policy paradigm for transformative change – this discussion is brought up in the empirical chapters of the thesis. Nevertheless, it is useful from the outset to review the conceptual framework of Diercks *et al.* (2019) to help position the research. The conceptual framework differentiates between different innovation policy paradigms along two key dimensions: (1) policy agenda (economic versus societal) and (2) understanding of the innovation process (narrow versus broad) – see Figure 1. This understanding builds on Edquist (2014), who argues that the objectives of innovation policy have to be separated from the understanding of the innovation process. This is similar to Boon and Edler who argue that 'innovation is not a goal in itself, but a means to a societal end' (2018:10). In general, a narrow economic policy agenda concentrates on economic policy objectives, such as growth, competitiveness, and jobs, by means of introducing new or improved product, processes, or services to the market. A broader societal policy agenda entails that innovation needs not only to sustain economic growth but also address a broader range of societal and environmental

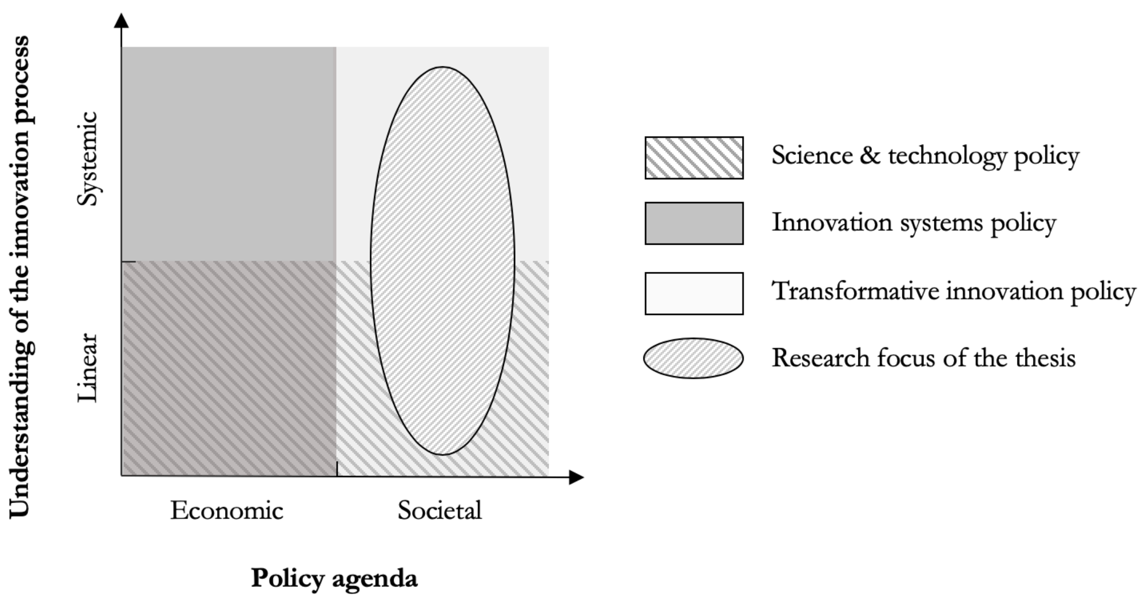

Figure 1 Framework to compare and contrast innovation policy paradigms

objectives. A narrow understanding of the innovation process mainly emphasises the supply-side of innovation and views innovation as a linear process of research and development (R&D) followed by demonstration and diffusion. Innovation processes are impeded by market failures, such as information asymmetries or knowledge spillovers, which justify policy intervention and the need for public support. The broader understanding of the innovation process is informed by a more systemic view of innovation, which entails that in addition to market failures, there is a range of systemic failures that need to be addressed in order to improve the interaction or relationships between the individual components comprising the innovation system. The broader understanding of the innovation process emphasises not only supply-side but also demand-side considerations, where innovation is then best characterised as an interactive learning process derived from the balance between the two distinct but complementary modes of learning and innovation: science, technology and innovation (STI) and doing, using and interacting (DUI). The application of the conceptual framework does not imply that innovation policy paradigms can be precisely positioned along the two dimensions, but rather that these can be compared relative to each other.[4] Such a categorisation is useful in two respects. First, it brings to light how innovation policy paradigms take shape and how the emergence of the policy paradigm for transformative change builds on earlier policy paradigms of science & technology policy and innovation systems policy. Second, the conceptual framework helps to illustrate the diverse representations and competing claims made by different groups of scholars that are currently shaping this newly created discursive space (see for instance Kuhlmann and Rip 2018, Mazzucato 2018, Schot and Steinmueller 2018).

1.2 Capabilities, networks, and directionality

Following Diercks *et al.* (2019), transformative innovation policy draws on three key features. First, transformative innovation policy has an aspiration for purposive and directional innovation that is currently missing in mainstream innovation policy. Second, the emerging policy paradigm is explicitly mission-oriented or challenge-led and aims to address a range of societal challenges. Third, acknowledging the nature and complexity of contemporary societal challenges, transformative innovation policy adopts a global outlook, which calls for new forms of participation and collaborative networks arrangements that may work between and across interrelated spatial scales. Importantly, the authors propose that transformative innovation policy must be grounded in an understanding of socio-technical systems change – an argument similar to that of Kuhlmann and Rip (2018) and Schot and Steinmueller (2018). Following the suggestion

[4] For a detailed description of the methodological considerations underpinning the conceptual framework, see Diercks (2017).

of Weber and Truffer (2017), a key question for research then becomes whether the systems of innovation approach can be revised to incorporate transformative change in socio-technical systems. Innovation scholars have previously called for systemic policy instruments that merge systems of innovation and sustainability transitions approaches (e.g. Foxon and Pearson 2008, Markard and Truffer 2008) but it is not immediately clear if and how the two may be reconciled.[5]

Building on the emerging policy paradigm for transformative change, this thesis takes steps towards the development of an innovation policy framework, which integrates insights from the system innovation perspective and opens up the systems of innovation approach to incorporate directionality and a strategic orientation of innovation systems that legitimises policy interventions in processes of transformative change to address societal challenges of the type of the SDGs.[6] As will be proposed in later chapters, next to the market and systemic failures that impede the performance of innovation systems, there is a need for innovation policy to incorporate a third category of 'transformational failures' to guide the direction of innovation and processes of transformative change in socio-technical systems (Weber and Rohracher 2012). Directionality presupposes the presence of capabilities needed to manage innovation and technological change, a dynamism that may accrue or diminish over time depending on the extent to which deliberate and continuous efforts are made to sustain it. Hence, a central premise of this research is that policy support for innovation capability formation, particularly in developing countries, is an essential prerequisite for implementing the SDGs. Innovation capabilities are built as a result of interactive learning derived from the balance between two complementary modes of learning: science, technology and innovation (STI) and doing, using, and interacting (DUI). These interactive learning processes are not necessarily spatially bounded but are increasingly enacted through the formation of global innovation networks spanning national innovation systems.

1.3 Research objectives

Focussing mainly on the needs and challenges of developing countries to create and accumulate the capacities needed to manage directional innovation and technological change, and firmly grounded in the emerging policy paradigm for transformative change discussed above, the research objective of the thesis is to integrate insights from the system innovation perspective and open up the systems of innovation approach to address not only economic policy objectives

[5] For instance, as argued by Alkemade *et al.*, 'transition policy and innovation policy fundamentally differ with respect to the type of innovation that is considered desirable … These incompatibilities arise from the fact that innovation policy often focuses on strengthening the current regime while transition policy [system innovation] has a regime-shift ambition … Alignment between transition policy and innovation policy can only be expected in the case where policy seeks to create new profitable industries that contribute to a more sustainable society' (2011:127).

[6] In this research, 'system innovation' refers to fundamental change in the configuration of socio-technical systems towards more sustainable modes of production and consumption. The system innovation perspective is described in more detail in section 6.2. The 'systems of innovation approach' is a concept of different ways to frame the systems in which innovation is developed, diffused, and used. The heuristic is described in section 2.3.

but also a broader range of societal and environmental objectives. Hence, conceptually, the research is concerned with refining the systems of innovation approach, and in particular revising the framework for national innovation systems, in this way, 'exploring avenues for making the IS [innovation systems] framework 'future-proof'' (Weber and Truffer 2017:102). Empirically, three separate case studies are used to validate different features of transformative innovation – *capabilities, networks, and directionality* – thereby taking steps towards the development of an innovation policy framework that explicitly incorporates directionality and a strategic orientation of innovation systems to address the nature and complexity of contemporary societal challenges.

1.4 Research question

Based on the research field presented above, the thesis is guided by the overall research question: *How can the systems of innovation approach be refined to incorporate a strategic orientation of innovation systems that legitimises policy interventions in processes of transformative change to address the United Nations Sustainable Development Goals?* In order to give a comprehensive answer to the research question, three broad sets of sub-questions have been developed and are explored in the empirical chapters.

1.5 Outline of the thesis

Chapter 2 – Systems of innovation approach and the national innovation systems concept

This chapter sets the stage for the thesis by providing a general introduction to the systems of innovation approach. It revisits the origins of innovation systems thinking and discusses its conceptual core and explanatory ambitions before describing the different but complementary ways to frame the systems in which innovation is developed, diffused, and used. It proceeds to present the national innovation systems concept – the primary framing adopted in the thesis – and discusses how the concept has been adopted in developed and developing countries, respectively. The chapter ends by elaborating on three emerging challenges and opportunities for innovation systems research. These research themes are then explored in the empirical part of the thesis.

Chapter 3 – Methodology and research design

This chapter presents the methodology and methods used in the thesis. It clarifies the ontological and epistemological position of the research and presents in detail the systematic combining approach followed in the thesis. The chapter then proceeds by describing the data collection methods employed in the thesis. This is followed by a brief description of the analytical procedures. The chapter ends with a discussion of the main methodological challenges of the research as well as the strategies used in the thesis to address these limitations.

Chapter 4 – Explaining interactive learning as determinant for innovation capability building: Firm-level evidence from the Brazilian innovation system

A first proposition of the thesis is that the creation and accumulation of innovation capabilities needed to pursue innovation in new and different directions along more sustainable development pathways are an essential prerequisite for implementing the SDGs. Support for innovation capability formation is particularly pertinent in developing countries, where national innovation systems are often fragmented and emerging. This chapter develops an understanding of how the capabilities needed to manage innovation and technological change are built as a result of interactive learning processes derived from the balance between the two distinct but complementary modes of learning and innovation: science, technology and innovation (STI) and doing, using, and interacting (DUI). Building on the literature on technological capabilities and recent insights from business innovation modes, the chapter goes beyond the traditional focus on internally and externally mediated learning and draws out the intra-organisational dimension concerning the interplay between science and engineering and how changes to this relationship influence innovation capability building. The findings of an in-depth qualitative case study for a subsidiary of the global biotechnology company, Novozymes, operating in the Brazilian bioethanol industry suggest that deliberate and continuous efforts to improve processes of interactive learning generates positive effects for the creation and accumulation of capabilities needed to manage innovation and technological change in more sustainable directions.

Chapter 5 – Enhancing international technology cooperation to address climate change: The role and function of innovation intermediaries in global innovation networks

A second proposition of the thesis is that interactive learning processes are increasingly enacted through the formation of global innovation networks spanning national innovation systems. The literature on national innovation systems has long argued that networks of actors and institutions situated around local knowledge bases intensify interactive learning and innovation. This view of interactive learning and innovation as spatially bounded phenomena is challenged as it is increasingly understood that these processes may be organised and work between and across interrelated spatial scales. A network view of innovation that transcends the effects of distance, in turn, raises interesting questions about other forms of proximity as a sufficient condition for interactive learning and innovation. Fully understanding this dynamic calls for an integrative view in which the national innovation systems concept is explicitly linked to the changing geography of innovation. This chapter furthers the understanding of how the formation of global innovation networks contributes to interactive learning in national innovation systems and in what way international technology cooperation complements the creation and accumulation of capabilities needed to manage innovation and technological change. Drawing on the strategic management literature and recent insights from economic geography, the first half of the chapter develops a basis for differentiating between forms of global innovation networks. The second half of the chapter maps the broader landscape of international technology cooperation in the context of climate change and probes the role and function of two distinct innovation intermediaries: (1) Climate Technology Centre and Network of the United Nations Framework Convention on Climate Change and (2) International Energy Agency Technology Collaboration Programmes.

Chapter 6 – System innovation of innovation systems: Towards an innovation policy framework for addressing the United Nations Sustainable Development Goals

A third proposition of the thesis is that transformative innovation policy must be grounded in an understanding of system innovation of socio-technical systems towards more sustainable modes of production and consumption. Based on the understanding derived from the previous chapters, this chapter takes steps towards the development of an innovation policy framework that draws on a combination of the systems of innovation approach and the system innovation perspective. This synthesis opens up the systems of innovation approach to incorporate directionality and a strategic orientation of national innovation systems to address not only economic policy objectives but also a broader range of societal and environmental objectives. The framework offers a new way to deal with the direction of innovation and technological change by proposing a method that operationalises the systemic problems that impede the transformative potential of national innovation systems and what type of systemic policy instruments that will best address these. The second half of the chapter provides an empirical assessment of the compatibility of the integrated policy framework with the United Nations Conference on Trade and Development Science, Technology and Innovation Policy Review programme and provides input to the work of the United Nations Technology Facilitation Mechanism established as part of the 2030 Agenda for Sustainable Development to legitimise policy interventions in processes of transformative change to address the SDGs.

Chapter 7 – Discussion and conclusion

This chapter concludes the thesis. A summary of the main research findings is presented, which are then discussed in relation to the overall research question of the thesis. This is followed by a presentation of the main contributions of the research. Plausible policy recommendations from the research are presented, and suggestions for a future research agenda are made.

2. Systems of innovation approach and the national innovation systems concept

Over the past decades, the systems of innovation approach has gained widespread use and is arguably the most influential framework guiding innovation scholars and policymakers today (Mytelka and Smith 2002). The appeal of the systems of innovation heuristic rests in its ability to identify the type of interacting components that are part of innovation systems in order to improve their attributes or the relationships between these (Carlsson *et al.* 2002). As explained by Lundvall, 'we use this concept as a focusing device in order to better understand how innovation affects economic development at the national level. Within this broad view many factors contribute to innovation and it might be seen as a problem that almost all aspects of society need to be brought in to explain the actual pattern of innovation' (2007:31). Notwithstanding its explanatory power, the systems of innovation approach is mainly oriented at optimising the innovation system to enhance its capacity to innovate and fulfil economic policy objectives. Therefore, in this research, the heuristic is suggested to suffer from a number of conceptual weaknesses.

First, the frame of reference for innovation has changed following the adoption of the 2030 Agenda for Sustainable Development and with it, the requirements for conceptual approaches that underpin innovation policy (see for instance Kuhlmann and Rip 2018, Mazzucato 2018, Schot and Steinmueller 2018). The expectation of innovation to cope with the nature and complexity of contemporary societal challenges entails substantial changes in the way societal functions are fulfilled (see for instance Elzen *et al.* 2004). A central premise of the thesis is that the systems of innovation approach requires conceptual refinement in order to incorporate a strategic orientation of innovation systems towards not only economic but also societal and environmental objectives. Second, it is increasingly acknowledged that innovation processes work between and across interrelated spatial scales and may be organised globally. Considering the growing impact of globalisation on innovation, the analytical limit of innovation systems to particular spatial scales, therefore, seems less and less appropriate. Consequently, innovation scholars are increasingly calling that the conceptual core of the systems of innovation approach to be reconsidered (see also Martin 2016, Weber and Truffer 2017).

This chapter aims to retrace the intellectual roots of the systems of innovation approach, discuss its conceptual core and explanatory ambitions, and finally take steps toward the development of a more integrative innovation systems framework to address contemporary societal challenges of the type of the SDGs. The remainder of the chapter is organised as follows. Section 1 revisits the origins of the innovation systems concept, discusses its intellectual roots, and describes the different but complementary ways to frame the systems in which innovation is developed, diffused, and used. Section 2 introduces the systems of innovation approach. Section 3 presents the national innovation systems concept – the primary framing adopted in the thesis – reviews the literature, and discusses how the framework has been adopted in developed and developing countries, respectively. Section 4 elaborates on emerging challenges and opportunities for innovation systems research and outlines how the systems of innovation approach is in need of conceptual refinement to underpin transformative innovation policy. This allows three lines of inquiry to be extracted, which are explored in the empirical chapters, thereby contributing to the development of an innovation policy framework that incorporates directionality and a strategic orientation of innovation systems to address the SDGs.

2.1 Origins of the innovation systems concept

Ever since Schumpeter clarified the importance of innovation as a key driver influencing economic growth and competitiveness, the fundamental question for innovation scholars has been to explain how change occurs (see Fagerberg 2006 for an introduction to the field of innovation studies). The Schumpeterian view of innovation emphasises the creation and accumulation of knowledge, leading to the implementation of new ideas.[7] Based on his evolutionary concept of 'creative destructions', Schumpeter argued that innovation had to be understood as processes of qualitative change driven by 'new combinations' of existing resources (Schumpeter 1942). During the 1960s, policymakers started to take an interest in the innovation imperative as a means for increasing economic growth and competitiveness. Early innovation studies tend to explain innovation to derive from one of two linear approaches: demand pull and technology push (see Rothwell 1992 for a summary of different 'linear' conceptualisations of innovation developed prior to the innovation systems concept). In the former, innovation and technological change were seen as driven by demand changes in the market. Innovation was, in a sense, pulled in certain directions in response to identified market needs and changing factor prices (Meyers and Marquis 1969). The notion that the market was the prime mover of technological change and innovation a basic reaction to demand changes was challenged (Mowery and Rosenberg 1979). In the latter approach, technology-mediated change was viewed as science-driven and pushed by investment in R&D (Bush 1945). Here, innovation was understood to emerge from science without prior consideration of particular market needs. Both approaches were deemed deterministic and failed to acknowledge the multiple determinants, non-linearities, and feedback loops that influence innovation.

[7] A widely used definition describes innovation as 'the implementation of a new or significantly improved product (good or service), or process, a new marketing method, or a new organisational method in business practices, workplace organisation or external relations (OECD 2005:46). This is based on the work of Schumpeter who classified innovation into five different types including new products, new methods of production, new sources of supply, the exploitation of new markets, and new ways to organise business.

It is evident that innovation covers a wide range of activities and processes, which can be described and categorised in various ways (for a general framework of concepts, definitions, and methodologies to measure innovation processes and research and experimental development activities, see the Oslo and Frascati Manuals of the OECD). A typical distinction is made between invention and innovation, where the former is the occurrence of an idea for a new product, process, or service, while the latter is the attempt to carry it out into practice. Therefore, innovation is broader than invention and includes the (commercial) application of new ideas. Another way to describe innovation is to differentiate between incremental and radical innovation. For instance, Dewar and Dutton suggest that 'radical and incremental describe different types of technological process innovations. Radical innovations are fundamental changes that represent revolutionary changes in technology … incremental innovations are minor improvements or simple adjustments in current technology' (1986:1422). On this matter, Freeman and Soete emphasised the diffusion of innovation, noting that 'during the 1950s and 1960s the evidence accumulated that the rate of technical change and economic growth depended more on efficient diffusion than on being first in the world with radical innovations and as much on social innovations as on technical innovations' (1997:301). Hence, a third way is to describe the extent to which innovation is diffused and used. To this end, Cooke proposes a three-stage process including invention, innovation, and diffusion where 'invention is the stage of the production of new knowledge, innovation is the stage of the first application of the existing knowledge within production, and diffusion in this model means the broad use of new technologies' (2003:4).

2.1.1 Intellectual roots of innovation systems thinking

The concept of innovation systems emerged against the backdrop of the growing discontent with neoclassical economic theory of technological change and of new conceptual developments at the margins of established social science disciplines, notably evolutionary economics, science and technology studies, and systems theory.[8] Weber and Hoogma pointed out at the time that 'a major convergence can be identified between evolutionary economics and the sociology of technology. ... the basic understanding of the process of technological change is quite similar, and – even more important – sufficiently open to introduce other perspectives. ... What is still missing is the actual integration in a single framework which would allow to investigate different cases from a wider perspective, and to bridge explicitly between economics and sociology with regard to technology studies' (1998:74). These strands of literatures are discussed in the following.

[8] The recent mapping and comprehensive bibliographic overview by Rakas and Hain (2019) of the changes in the knowledge production and output is useful to consider the development of innovation systems research over the past decades.

2.1.2 Evolutionary economics – technological regimes and paradigms guiding innovation and technological change

Important steps toward a more systemic understanding of innovation were made during the 1970s and 1980s, where innovation and technological change were studied based on the economic operationalisation of evolutionary mechanisms (see for instance Nelson and Winter 1982). The more integrative understanding of innovation processes that emerged during this period fundamentally challenged one of the core principles of neoclassical economics: that economic agents can maximise profits because they have perfect information about the different options available to them; and further, that collective macro-level phenomena can be understood as an aggregation of individual behaviour and micro-level decisions (Weber and Truffer 2017). A key argument in the evolutionary economics literature, and which is central to the concept of innovation systems, is that innovation and technological change are not introduced from a point source, but take place through co-evolutionary processes of selection, variation, and retention. For instance, this evolutionary impetus is incorporated by Nelson and Winter (1977) in their conceptualisation of 'natural trajectories' that guide technological change by creating stability and a sense of direction for innovation. Breaking with the prevailing neoclassical economic thinking, firms do not have perfect information, nor operate on the basis of rational utility maximisation models, but make use of search heuristics, rules, routines, and cognitive frameworks to make sense of the world. To Nelson and Winter, these shared rules and routines predominantly guide economic behaviour and organisational activity regarding innovation: 'Our concept [technological regimes] is more cognitive, relating to technicians' belief about what is feasible or at least worth attempting ...The sense of potential, of constraints, and of not yet exploited opportunities, implicit in a regime focuses the attention of engineers on certain directions in which progress is possible, and provides strong guidance as to the tactics likely to be truthful. In other words, a regime not only defines boundaries, but also trajectories to those boundaries' (1977:57). Hence, rather than searching in all directions, practitioners align their search heuristics in specific directions where they expect to find better results. These self-reinforcing processes of technological regimes infer a powerful search heuristic that leads to the improvement of prevalent practices and experiences.

On an industry level, because innovative activities in firms and knowledge institutes are focused more or less in the same direction, they add up to natural trajectories, resulting in incremental technological change that progresses in particular directions in a path-dependent manner. Nonetheless, importantly, Nelson and Winter do infer that the shared rules and routines of firms differ slightly, thus resembling evolutionary variation, the outcome of which is primarily determined through (market) selection. This is similar to Dosi (1982), who proposes that innovation processes progress along particular technological trajectories defined by a 'technological paradigm', while discontinuities are associated with the emergence of a new paradigm. Analogous to the Kuhnian view of normal science in scientific paradigms, Dosi defines a technological paradigm as a 'model and pattern of solution of selected technological problems based on selected principles derived from natural sciences and selected material technologies', and a technological trajectory as 'the pattern of normal problem-solving activity (i.e. of progress) on the ground of a technological paradigm' (ibid:152). Strong vested interests and sunk costs contribute to the permanence of these networks of power, which gives rise to technological momentum that impedes radical innovation. Dosi argues that demand changes do affect the direction of technological trajectories; however, innovation occurs within the boundaries of the technological paradigm. This view of technological progress along particular trajectories is similar to the concept of 'technological imperatives' suggested by Rosenberg (1969). Here, innovation is focused in particular directions towards technical problems that are within the capacity of society to solve. Relatedly, Levinthal argues that innovation results from new technological configurations being applied to the selection criteria of new niches while the gradual or rapid pace of this development is driven by the resources available within that niche (1998).

Combined, evolutionary economics suggest that technological regimes and paradigms function as important retention mechanisms for the direction of innovation and technological change. For instance, Dosi argues that 'once a path has been selected and established, it shows a momentum of its own' (1982:153). Building on long wave theory of economic development, Freeman and Perez (1988) explore momentous technological change at the level of the economy through shifts in techno-economic paradigms. According to the authors, 'some changes in technology systems are so far-reaching in their effects that they have a major influence on the behaviour of the entire economy. Clusters of innovations typically emerge from changes in the relative cost structure in the existing techno-economic paradigm. A change of this kind carries with it many clusters of radical and incremental innovations ... it has pervasive effects throughout the economy' (ibid:47). Interrelated sets of technologies, industries, and infrastructural networks develop feedback and lock-in mechanisms causing persistent change. The new techno-economic paradigm initially emerges as a reaction to tensions within the old but technological momentum acts as a powerful deterrent for change. Only after a long period of gestation and competition will new innovations lead to structural adjustment. These technological revolutions, causing social and institutional change, will eventually result in a new techno-economic paradigm (Perez 1983).

The strong analogy to natural selection (Darwinism) in evolutionary economics suggests that innovation and technological change progress in specific directions predetermined by natural forces. The evolutionary impetus of innovation and technological change has been vigorously debated, and critics argue that 'natural trajectories' are self-fulfilling prophecies only because these are continually reinforced by the belief and expectations of actors and institutions. The role of the market is strongly emphasised in the literature as guiding the selection, variation, and retention of innovation. This somewhat deterministic view of innovation and technological change is perhaps the main weakness of this literature. An important critique is that a sole focus on the market as a selection mechanism fails to explain how incremental and radical innovation often emerge in the absence of articulated demand. Besides, evolutionary economics tend to focus on the emergence and diffusion of new technology and often neglect the impetus, persistence, and self-reinforcing processes of existing technologies. New technologies do not necessarily compete with existing technology but may have ancillary and complementary features resulting in hybrid technology forms (Levinthal 1998). Hence, innovation not only results from demand changes but also from co-evolutionary changes in the selection environment. Innovation and technological change are therefore not solely determined by market forces but also by various institutional structures and scientific knowledge available within the existing technological regime or paradigm (MacKenzie and Wajcman 1999). It is at this point the connection between evolutionary economies and science and technology studies becomes relevant for a more systemic understanding of innovation.

2.1.3 Science and technology studies: from technological determinism to social constructivism

A related cornerstone of innovation systems thinking is the new conceptual developments in science and technology studies (STS) that emerged in the 1980s, which advocated a more social constructivist approach to innovation and technological change (see Smith and Marx 1994 for an introduction to the field of STS). This literature draws on a variety of interdisciplinary perspectives including 'social construction of technology' (e.g. Bijker *et al.* 1987), 'actor-network theory' (e.g. Latour 1987), and history of science and technology (e.g. Hughes 1987). STS strongly reject technological determinism and the reductionist view that technology is driven by an internal autonomous logic. On the contrary, STS consider technology and society as co-constructed through the creation of linkages and heterogeneous networks (Smith and Marx 1994). This view implies a dynamic relationship between technology and its social environment. The notion of technology must be understood as broader than the artefact itself and includes the social, cultural, and institutional connotations of technological configurations. Hughes (1987) metaphorically thought of technology as embedded in a 'seamless web', indicating that its functioning depends on various interconnected elements. Hence, in the field of STS, technology is not assumed to be autonomous to the social world. Technology shapes its social environment and is in turn shaped by it. Neither is the sole determinant of the other: the two codetermine each other.

Scholars of the 'social construction of technology' study innovation and technological change through interpretative and socio-cognitive processes (Bijker *et al.* 1987). When a new technology emerges in society, there is initially much uncertainty about its form and function (Arthur 1989). Practitioners have different perceptions about problems, solutions, and meanings of new technology but gradually consensus emerges. This 'interpretative flexibility' eventually stabilises in a dominant, though not necessarily superior, technological design, while alternative interpretations cease to exist (David 1985). The closure and stabilisation of the technological design are the result of socio-cognitive processes, the outcome of agency and interaction between a variety of social groups rather than determined by an independent technical logic (Pinch and Bijker 1984). Therefore, in this stream of literature, particular attention is paid to how different social groups such as engineers, users, and policymakers are involved in the development of new technology.

Actor-network theory analyses relational ties in networks and reveals the complexities and contingencies that are often overlooked in other accounts of innovation and technological change. Drawing on extensive case studies, actor-network theory describes how technology initially emerges as heterogeneous configurations in networks consisting of human and nonhuman elements and linkages (Callon 1987). Innovation is here understood as the further accumulation of heterogeneous elements and linkages into working configurations (Latour 1987). Similar to other STS disciplines, actor-network theory explores the interactions between the 'social' and the 'technological' in a deeply interactive and relational fashion. However, the emphasis in this literature is not on causality but more on the resulting 'heterogeneous engineering' and mapping of relatively stable yet colliding elements in actor-networks. Whereas the social construction of technology emphasises how social and cultural forces strongly influence technological change, actor-network theory proposes a more balanced account: 'in explanations of technological change the social should not be privileged. It should not be pictured as standing by itself behind the system being built and exercising a special influence on its development. ... Other factors – natural, economic or technical – may be more obdurate than the social and may resist the best effort of the system builder to reshape them. Other factors may, therefore, explain better the shape of the artefact in question and, indeed, the social structure that results' (Law 1987:113).

In his influential work on the history of science and technology, Hughes (1983) helped define the difference between social and technological determinants of change. The author described how large technological systems are networks of massive proportions and complexity. Strong vested interests, stranded assets, and sunk costs contribute to the growth and permanence of these systems, which give rise to technological momentum: '[large technical systems] have a mass of technical and organizational components, they possess direction, or goals and they display a rate of growth suggesting velocity' (Hughes 1987:76). Technological momentum impedes the support of more radical innovations, resulting in incremental and path dependent change. Hence, it is only when substantial problems arise, which cannot be solved within the context of the existing technological system, that radical innovations are considered. The often-disruptive change, resulting from radical innovation may eventually overthrow the old and bring about a new technological system. Importantly, although technology is placed at the centre of change, Hughes rejected a deterministic character of technology and argued that social development shapes and are shaped by technology. To Hughes, technological momentum was an integrative concept that gives equal weight to social and technical forces. To summarise, the strength of STS lies in its societal embedding of technology. Combined, this literature has contributed to a greater understanding of the social processes involved in innovation and technological change.

2.1.4 Systems theory and the socio-technical understanding of innovation

A third important source of inspiration for the innovation systems concept is rooted in general systems theory, which has gained prominence in analysing adaptive patterns of interaction between different system components and emergent properties (see for instance Levinthal 1998, Gunderson and Holling 2001, Rotmans *et al.* 2001). Systemic change is often depicted as a sigmoid-curve illustrating the nonlinear sequence of three alternating stages: emergence, growth, and maturity. This perspective suggests a model of non-equilibrium, where slow, gradual, and incremental changes are followed by rapid change as co-evolutionary processes are reinforced, leading to a new dynamic and relatively stable equilibrium. These non-linear interactions between individual system components lead to the emergence of qualitatively different higher-order properties that cannot be explained by simple aggregation as proposed by mainstream neoclassical economics. Among other things, this understanding of systemic change has given rise to the multi-level perspective on socio-technical systems and associated approaches of strategic niche management and transition management (see Loorbach *et al.* 2017 for a comprehensive review of this literature). Socio-technical systems are conceptualised around functional domains and comprise clusters of elements including technology, policy, regulation, science, markets, infrastructure, etc. (Rip and Kemp 1998). The multi-level perspective organises socio-technical systems into three heuristic analytical levels: niches, regimes, and landscapes. The connection between the three levels can be understood as a 'nested hierarchy' with regimes structurally embedded in landscapes and niches within regimes (Geels 2002). The niche level acts as 'protective spaces' that nurture new configurations (technology, user practices, and regulatory structures), which are not competitive in terms of cost and performance at the regime level (Schot 1998).

Experimentation with these loosely structured configurations eventually stabilise and start to compete with the existing socio-technical regime through shared expectations, learning processes, and network building (Kemp *et al.* 1998). The landscape level works to reinforce existing trajectories in socio-technical regimes but can also be a source of pressure for change, prompting responses from within the regime or the consideration of niche alternatives. Hence, innovation and technological change result from shifts in the landscape level or by tensions in the socio-technical regime and come about when niches link up with and reinforce these processes (see for instance Geels and Schot 2007, Schot and Geels 2008, Smith and Raven 2012).

2.1.5 Towards a systemic understanding of innovation

Despite the more integrated understanding on innovation and technological change that emerged in the 1980s – exemplified for instance by the chain-linked model of innovation proposed by Kline and Rosenberg (1986) – theory and conceptual development were deemed deterministic and failed to acknowledge the systemic nature of innovation (Smith 2000). As emphasised by Freeman, 'a satisfactory theory on technical change must embrace a taxonomy of innovation which recognises the qualitative differences between different types of innovation and their systemic interdependencies' (1992:77). In response to the limitations of the linear models of innovation, a new paradigm emerged that viewed innovation in systems comprised of different actors, interacting in networks under a particular institutional setting. Innovation systems scholars have since emphasised the distributed but coordinated agency that underpins innovation processes: a systemic view of innovation that extends beyond the supply-side to include demand-side considerations by considering the diffusion, implementation, and use of innovation.

Systems of innovation have a narrow and broad meaning (see Table 1). Both framings are viewed as analytical policy tools to link innovation to economic performance at the national level. The main difference between these can be ascribed to a narrower or broader definition of the concept, the main focus of the analysis, and the elements included in studying innovation systems. In the former, the innovation system is narrowly defined as the networks of firms and knowledge institutes that develop and diffuse scientific and technological knowledge (Nelson 1993). The broader definition adopted by Lundvall (1992) places user-producer interaction at the centre of analysis, emphasising interactive learning and capacity building in networks comprised of a broader and more diverse set of actors and socio-economic institutions. Clearly, the division between the narrow and broad framing is not sharp, but it is useful in providing a more integrated view of innovation. In an attempt to reframe and unify the initial framings and conceptual approaches, Edquist suggests that 'if we want to describe, understand, explain – and perhaps influence –

processes of innovation, we must take all important factors shaping and influencing innovations into account (1997:2). Subsequently, several conceptual approaches were developed that, while grounded in a systemic understanding of innovation, considered different ways to influence the development and diffusion of knowledge and technology. Combined, these interpretations of innovation systems laid ground to the systems of innovation approach, a heuristic of different but complementary ways to frame the systems in which innovation is developed, diffused, and used. Common for these conceptual approaches is that these deviated from the linear models of innovation and embraced a more systemic understanding of innovation (Carlsson *et al.* 2002).

Table 1 Narrow versus broad understanding of innovation systems

	Narrow:	Broad:
Actors	Firms and knowledge institutes supported by government	A broader and more diverse set of actors and socio-economic institutions
Activities	Development and diffusion of scientific and technical knowledge	Interactive learning, innovation, and capacity building
Mode of innovation	Science, technology and innovation (STI)	Science, technology and innovation (STI) and doing, using and interacting (DUI)

Author's elaboration based on Freeman (1978), Lundvall (1992), Nelson (1993), and Edquist (1997)

2.2 Systems of innovation

The systems of innovation approach provides a robust framework for innovation scholars and policymakers to identify the types of interacting components and relationships that are part of the innovation system to enhance its capacity to innovate and fulfil economic policy objectives (Edquist 2006). The boundaries of the innovation system are defined based on the structural dimensions of interacting system components comprising the system and their relation to the external environment. Based on the structural analysis of the innovation system, different market and systemic failures can be identified and addressed through a variety of policy instruments, such as R&D subsidies, tax incentives, matching grants, or intellectual property rights systems that improve the attributes of individual system components or the relationships between these.[9] Although various framings of innovation systems have emerged over the decades, it is fair to say that the national innovation systems approach has been the guiding framework for innovation research and has strongly influenced policy prescriptions since the early 1990s (Fagerberg and Sapprasert 2011). Despite the growing impact of globalisation (see for instance Niosi and Bellon 1994 and Archibugi and Iammarino 1999), as discussed by Freeman at the time,

[9] Compared to structural analysis, which focuses on mapping and evaluating the individual components of the system and its capacity to innovate, functional analysis centres on the functions that are important for innovation systems to perform well (see Hekkert et al. 2007, Bergek et al. 2008).

'nation states, national economies and national systems of innovation are still essential domains of economic and political analysis' (1995:45).[10] Similarly, Arocena and Sutz emphasise the importance of studying innovation systems at the national level, 'even if globalization heavily affects many - if not all - of these issues and the overall climate for innovation at country level, there is always room for 'national influences' that can take the form of public policies - at macro, meso or micro level - and can also be the outcome of distributed initiatives coming from the most diverse social actors' (2000:56). Notwithstanding their explanatory power, early concepts of national innovation systems came under increasing criticism for being vague, open to misinterpretation, and inclusive to the point of being impractical (Miettinen 2002). It was increasingly suggested that the macro level focus of the national innovation systems concept missed the more important underlying micro-level processes through which innovations come about. Therefore, research efforts were devoted to understanding how innovation systems operate independently of any scalar or geographical delimitations This diverse work placed a growing emphasis on system processes, network relations, and the spatial dynamics between actors and institutions, leading to insight into how knowledge and technologies develop and diffuse and how innovation systems evolve over time. Before turning to the presentation of the national innovation systems concept, these different framings of innovation systems are introduced and discussed.

The first of these is by Carlson and Stankiewicz who defined a technological system (commonly referred to as a technological innovation system) as, 'a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology' (1991:111). The second is the sectoral innovation system approach proposed by Breschi and Malerba (1997), who suggest that innovation is best understood by considering a set of products and a distinct set of actors who interact through networks in the development, production, and sale of those products. Importantly, Malerba (2002) suggests that examining innovation at the sectoral level offers greater insight into how sectors and thus sets of technologies interact and change over time. These actors hold sector-specific knowledge, and their interactions are influenced by institutions that may have both national and international dimensions. Responding to the development of these new conceptual approaches, Lundvall argues that these are not necessarily in conflict with the national innovation systems concept. To the contrary, 'the analysis of technological systems has been especially useful in analysing how new technologies emerge. The sectoral system

[10] The national innovation systems concept was further boosted by the book 'The Competitive Advantage of Nations' in which Michael Porter argued that national prosperity, 'is created, not inherited. It does not grow out of a country's natural endowments, its labour pool, its interest rates, or its currency's value, as classical economics insists … [rather a nation's competitiveness] depends on the capacity of its industry to innovate and upgrade' (1990:73) (see also Furman *et al.* 2002 for a similar analysis).

approach is unique among the different approaches in not defining as analytical object a vertically integrated system' (2010:319). The third approach is the regional innovation system proposed by Cooke *et al.* (1997) who suggest that innovation is best understood as local and spatially bounded processes. Lundvall explains that the regional innovation systems approach is not in disagreement, but rather complements the national innovation systems concept: 'it uses the fact that some knowledge is local and tacit to explain that innovation systems are localised' (2010:319). Indeed, according to Lundvall, both geographical approaches (national and regional) emphasise that user-producer interaction and innovation processes benefit from co-location in the learning economy.

There is still much discussion on how innovation systems should be framed. Although the systems of innovation approach initially emerged as a critical response to the dominant framing of the national innovation system, Lundvall maintains that 'these [framings] are not alternatives to the analysis of national systems. They have important contributions to make to the general understanding of innovation in their own right … [and therefore should be seen as complementary to the national innovation systems concept] … to compare sectoral, regional and technological systems across nations is often an operational method for understanding the dynamics at the national level' (2007:100). Meuer *et al.* suggest that innovation scholars need to consider the co-existence of different innovation systems in order to develop a more integrated understanding of innovation systems and 'to identify points of inter-sections between innovation systems, to specify similarities and differences in the innovative capabilities of co-existing innovation systems, and to determine the function of individual innovation systems in a broader innovation system' (2015:890) (see also Fischer 2001 and Fromhold-Eisebith 2007 for similar lines of argument).

It is the opinion of this author that identifying the relevant individual system components, interpreting their interrelations, and setting the appropriate boundaries of the innovation system are methodological choices of the researcher. Therefore, the framing of innovation systems largely depends on the research objective and analytical inquiry. In this way, the systems of innovation approach can be understood as based on a 'model of reality' designed for analytical purposes. As argued by Bergek *et al.* 'we can, thus, think of the contexts [conceptual boundaries] as mutually excluding conceptual magnifying glasses, which each brings specific things to the foreground and which together provide a more complete picture of an empirical case' (2015:11). This is somewhat similar to Lundvall *et al.* who argue, 'we see a complementary role for analyses at different levels of aggregation and it is important to note that the analysis of sectoral and regional innovation systems bring in a meso level that can mediate between the micro and macro dynamics' (2009:8) (see also Markard and Truffer 2008 and Castellacci 2009 for a similar line of argument on the relationship and complementarity between different innovation systems approaches).

2.3 National innovation systems

The study and analysis of national innovation systems have coincided with several broader shifts in the literature over the last decades including (1) departure from macro institutional explanations to a focus on specific system processes, (2) adoption of the framework as a template for economic development and catching-up, (3) incorporation of the changing geography of innovation imposed by globalisation (see Balzat and Hanusch 2004, Soete *et al.* 2010, Watkins *et al.* 2015 for discussions on how the concept has developed over the past three decades). The aim of the following subsections is to review the literature on national innovation systems, thereby providing an essential background for understanding how the framework has developed since the early 1990s and to provide a basis for discussing whether the conceptual core of the systems of innovation approach is appropriate for addressing contemporary societal and environmental challenges.

2.3.1 Early concepts and approaches

The framework for national innovation systems was originally developed to explain economic development based on differences in innovative and technical performance between countries (Godin 2009). The rationale for studying national innovation systems was that 'innovation and technology development are the result of a complex set of relationships among actors in the system, which includes enterprises, universities and government research institutes' (OECD 1997:7). A national innovation system was generally understood to comprise a range of actors interacting in networks under a particular institutional setting – see Box 1. What these definitions have in common is: first, a reference to socio-economic institutions; second, a focus on the development and diffusion of knowledge and technology; and third, several of the definitions refer to specific system components and the relationships between these.

Freeman (1987) was perhaps the first to use the national innovation systems concept in his analysis of how Japan acquired major competitive advantages over Europe and the United States in the post-war era.[11] Freeman explained that the basis for increased competitiveness and economic development in Japan was due to its specific institutional settings in which consecutive governments played a central orchestrating role in strengthening science–industry linkages between universities and research institutes, on the one hand, and private sector organisations, on the other (see also Mowery and Oxley 1995 for an in-depth analysis of the role of national innovation systems in fostering economic development in Japan and other East Asian countries).

[11] There is some uncertainty regarding the origins of the national innovation systems concept. Shariff (2006) traces the first use of the concept back to an unpublished paper by Freeman (1982). However, Freeman himself cites Friedrich List as one of the first scholars to express the idea of a national system of innovation as he discussed the importance of innovation and knowledge as drivers of national economic performance: 'the idea actually goes back at least to Friedrich List's conception of 'The National System of Political Economy' (1841), which might just as well have been called 'The National System of Innovation' (1995:5).

Box 1 Early definitions of systems of innovation

'… the network of institutions in the public and private sectors whose activities and interactions initiate, import, modify and diffuse new technologies' (Freeman 1987:1)

'… a system of innovation is constituted by elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge … and are either located within or rooted inside the borders of a nation state' (Lundvall 1992:3)

'… a set of institutions whose interactions determine the innovative performance, in the sense above, of national firms' (Nelson 1993:4)

'… A national system of innovation is the system of interacting private and public firms (either large or small), universities, and government agencies aiming at the production of science and technology within national borders. Interaction among these units may be technical, commercial, legal, social, and financial, in as much as the goal of the interaction is the development, protection, financing or regulation of new science and technology' (Niosi *et al.* 1993:208)

'… the national institutions, their incentive structures and their competencies, that determine the rate and direction of technological learning (or the volume and composition of change generating activities) in a country' (Patel and Pavitt 1994:78)

'… that set of distinct institutions which jointly and individually contribute to the development and diffusion of new technologies and which provides the framework within which governments form and implement policies to influence the innovation process. As such it is a system of interconnected institutions to create, store and transfer the knowledge, skills and artefacts which define new technologies' (Metcalfe 1995:463)

Building on the pioneering work of Freeman, as previously mentioned, two dominant approaches for analysing national innovation systems subsequently took hold (see Table 1). One approach viewed the national innovation system as the networks of companies and knowledge institutes that developed and diffused scientific and technical knowledge (Nelson 1993). National strategic priorities, such as the nuclear energy and space programmes developed in the 1960s and 1970s, created a strong belief in the top-down, centralised control of scientific and technological knowledge production as well as support for regulatory environments conducive to entrepreneurialism and risk-taking. The narrow view of the national innovation system emphasised national science and technology institutions and is based on what Nelson and Rosenberg identified as, 'a strong belief that the technological capabilities of a nation's firms are a key source of their competitive prowess, with a belief that these capabilities are in a sense national and can be built by national action' (1993:3). This view on science-driven, technology-mediated change draws heavily on science, technology and innovation (STI) relationships and ideally involve controlled environments in laboratory settings, which permit a systematic accumulation of deliberately created findings, resulting in the production and codification of scientific and technical knowledge.

This understanding of the innovation process, emphasising the use of scientific methods and principles, which can be measured indirectly through proxies such as firm-level R&D expenditures, education levels, and patents is widespread today (see for instance the OECD Oslo and Frascati Manuals). The broader approach adopted by Lundvall (1992) and the so-called 'Aalborg group' emphasised interactive learning and capacity building processes in networks comprising a more diverse set of actors, essentially encompassing all parts and aspects of the economic system and institutional set up as far as these have an impact on innovation processes. The broader view of national innovation systems emphasise that not all innovation processes are science-based and purely STI-driven. Knowledge and capabilities gained from experience-based modes of learning and doing, using and interacting (DUI) relationships play an equally important role for innovation, interactive learning, and capacity building processes (Caraça *et al.* 2009).

2.3.2 Impact of the national innovation systems concept

Analyses of national innovation systems have over the past decades gained wide traction not only in academia but also among policymakers, who seek to understand the dynamics of interactive learning and institutional determinants that influence national innovative performance (Freeman 2002). Feinson notes that the national innovation systems concept is perceived by innovation scholars and policymakers, 'as having great potential both as a source of understanding of the roots and primary causes of the gulf in economic development, as well as a powerful conceptual framework that can produce policies and institutions capable of bridging that gulf' (2003:14). In particular, the OECD has played a vital role in the uptake and application of the framework. This point is emphasised here because the national innovation systems concept has been widely adopted as a tool for innovation policy in the OECD as much as innovation policy has served as a source of inspiration for research. This co-creation process was facilitated not least by the double role that several prominent innovation scholars played in formulating scientific concepts and methods, on the one hand, and shaping policy discourses on the other.[12]

However, although the concept enjoyed widespread uptake in policy and decision-making processes, innovation scholars over time tied different meanings to key terms and definitions. This interpretative flexibility naturally involved a trade-off between simplicity and realism, resulting in a certain degree of fuzziness of key concepts. For instance, whereas Lundvall has admitted to 'some distortion of the concept' (2007:2), Edquist (2005) argues that the national innovation systems concept, 'should be labelled an approach or conceptual framework rather than

[12] For instance, it is evident that Christopher Freeman, Bengt-Åke-Lundvall, Keith Smith, and Luc Soete have all worked at or advised the OECD on policy matters related to national innovation systems (Sharif 2006).

theory' (2006:186). Cooke makes a similar critique: 'the systems approach, as has been said earlier, only provides an analytical framework, and is not itself a substantive theory' (2003:6). Teixeira (2014) summarises some of the early criticisms made with regard to the adoption of the national innovation systems framework and argues it is still subject to the narrow view in terms of concepts and policy practice. Lundvall responds to these and other criticisms and asserts that 'using the perspective helps to see, understand and control phenomena that could not be seen, understood or controlled without using this (or a similar) concept. In this sense, the national innovation systems concept does what theory is expected to do: it helps to organize and focus the analysis, it helps to foresee what is going to happen, it helps to explain what has happened and it helps to give basis for rational action' (2007:18). Drawing on the innovation systems literature and in particular the contributions of Chaminade and Edquist (2010) and Wieczorek and Hekkert (2012), the next subsection describes the national innovation system based on four structural dimensions: (1) actors, (2) institutions, (3) networks, (4) infrastructures.

2.3.3 Actors, networks, institutions, and infrastructures: a framework for national innovation systems

There is general agreement that *actors* play an essential role in the performance of national innovation systems but that the activities and dynamics of these are interrelated with the broader macro-economic and regulatory context.[13] Hence, a key point in innovation system studies is that individual actors are not considered in isolation, but rather 'how they interact with each other as elements of a collective system of knowledge creation and use, and on their interplay with social institutions' (Smith 1994:3). Early work on national innovation systems places firms as the main actor through which innovations are developed and diffused. Firms were regarded as the key component that introduced new ideas in the form of new product, processes, and services in national innovation systems (OECD 2002). Later work would challenge the firm-centred approach in the analysis of national innovation systems with related concepts such as the triple and the quadruple helix model of innovation, moving away from a singular focus on academia, industry, and government to the direct engagement with a broader more diverse set of actors including civil society (Etzkowitz and Leydesdorff 2000, Carayannis and Campbell 2009). For these concepts, however, the dominant focus on science-industry linkages and collective collaboration and feedback between firms and knowledge institutes comprising the national innovation systems still predominate. Another central actor is the knowledge institutes that undertake research and provide

[13] Some innovation scholars describe the actors of innovation systems from the perspective of the role they play in innovation processes such as users, producers, intermediaries, supportive organisations, etc. Others categorise these based on their role in economic activities. Considering the systemic nature of innovation, implying dynamic feedbacks and loops between various stages of the innovation process, the difference between users and producers of innovation is blurred. Therefore, in this thesis, subcategories of actors are primarily delineated based on their role and function in the economy: firms, knowledge institutes, government, other entities, civil society, etc. (see Table 2).

higher education to the scientists and engineers that repopulate the innovation 'ecosystems'. For instance, Nelson (1993) argued that the strength of the national innovation system in the United States was attributed to strong government support for basic research, high levels of defence spending leading to research spin-offs, and a university research system that was able to effectively connect R&D activities to emerging high-tech industries (see also Mowery 1998, Owen-Smith *et al.* 2002). A third actor, governments, play an essential supporting role in national innovation systems, providing incentives and regulatory support that create the right framework conditions for firms and knowledge institutes to thrive (e.g. well-functioning patent laws, intellectual property rights, good infrastructure, access to research funding and finance, and a healthy entrepreneurial climate, etc). For instance, Freeman (1987) found that Japanese governments placed considerable emphasis on the development of strong science-industry linkages, provision of regulatory protection, and funding for basic and applied research coupled with strategic investments in high-tech sectors, such as automobiles and consumer electronics.

As previously mentioned, innovation is conceptualised not as a series of isolated events but as processes of interactive learning enacted through networks of actors operating under a particular institutional setting. A second structural dimension of national innovation systems is, therefore, *networks* which can be differentiated at the level of the system or between the individual system components. A third structural dimension is the *institutions,* which make up the common habits, practices, routines, and rules that determine the interaction between the actors comprising the national innovation system. Institutions may refer to hard institutions, such as financial, judicial, and regulatory systems, and to soft institutions, such as social norms and customs that together dictate 'the rules of the game in a society or, more formally, are the humanly devised constraints that shape human interactions' (North 1991:97). Institutional imprints differ strongly between national innovation systems, but are important to consider in relation to how they manifest interaction between the individual components of the system (Niosi 2002). For instance, Ray (1989) finds that the institutional frameworks in countries such as Germany, Sweden, and Switzerland proved to be particularly effective in their support for private sector financing of R&D with an industrial base dominated by large firms engaged in chemicals and advanced machinery. In contrast, in other European countries, such as Italy, Spain, and Portugal, institutional linkages were weak or missing, resulting in relatively more fragmented national innovation systems (Patel and Pavitt 1994). As an additional fourth structural dimension of national innovation systems, scholars have recently started to add various types of *infrastructure* that influence innovation processes. Following Wieczorek and Hekkert (2012) three different types of supporting infrastructure (physical, knowledge, and financial) are considered in this research.

Table 2 Framework for national innovation systems

	Subcategories of system components categorised according to structural dimensions
Actors	**Firms:** entrepreneurs, small and medium-sized enterprises, large firms, multinational companies, etc. **Knowledge institutes:** universities, research institutes, technical schools, etc. **Government:** ministries, departments, agencies, intergovernmental organisations, etc. **Other entities:** legal and financial organisations, banks, trade unions, donors, consultancies etc. **Civil society:** citizens, civil society and non-governmental organisations, cooperatives, grassroots etc.
Networks	Interaction at the national innovation system level Interaction between individual system components
Institutions	**Hard**: rules, laws, regulations, etc. **Soft:** customs, common habits, routines, established practices, traditions, norms, etc.
Infrastructures	**Physical:** artefacts, instruments, machines, roads, buildings, networks, bridges, harbours, etc. **Knowledge:** digital network infrastructures, online platforms, knowledge management systems, etc. **Financial:** subsidies, financial programmes, grants, etc.

Based on Chaminade and Edquist (2010) and Wieczorek and Hekkert (2012)

A framework for national innovation systems categorised according to the four structural dimensions is presented in Table 2. The next subsection proceeds to discuss how the framework for national innovation systems has been adopted as a template for economic development and catching-up in developing countries.

2.3.4 National innovation systems as a roadmap for economic development and catching-up

It is evident that the framework for national innovation systems has largely been developed based on empirical evidence derived from developed countries and in particular those comprising the OECD (see Shariff 2006 for an in-depth analysis of the emergence and development of the national innovation systems concept).[14] Although it is generally accepted that innovation plays a central role in economic development, research on national innovation systems in the context of developing countries has until recently been scarce and underdeveloped (Lundvall *et al.* 2009). Arocena and Sutz argued at the time that although most empirical research that contributed to the development of the national innovation systems concept was from developed countries, 'its applicability is not confined to those countries. In fact the NSI approach can be useful for studying the specifics of innovation processes and policies in the South, as well, and can draw attention to similarities and differences from those in the North' (2000:55). Hence, amid increasing concerns about the impacts of globalisation, multinational corporations, and the growing economic disparity between the global North and South, the framework for national innovation systems emerged as a roadmap for economic development and template for catching-up in the world economy.

[14] Based on econometric analysis of mainly firm-level surveys, previous studies have analysed the performance of national innovation systems in developed countries, such as those in Japan (Motohashi 2005), Germany (Kaiser and Prange 2004), Norway (Fagerberg *et al.* 2009), Switzerland (Marxt and Brunner 2013), France (Amable and Hancké 2001), and Spain (Fernández-Esquinas and Ramos-Vielba 2011).

In the late 1990s and 2000s, the framework was applied to the so-called newly industrialised countries including Singapore (e.g. Wong 1999, Wong 2003, Parayil 2005), South Korea (e.g. Kim *et al.* 1999, Lim 2000, Yim and Kim 2005), and Taiwan (e.g. Lee and Von Tunzelmann 2005, Chen 2007, Dodgson *et al.* 2008) and later to emerging economies such as Brazil (e.g. Viotti 2002, Franco *et al.* 2011, Suzigan and Albuquerque 2011), China (e.g. Liu and White 2001, Gu and Lundvall 2006, Motohashi and Yun 2007, Xiwei and Xiangdong 2007), India (e.g. Aggarwal 2001, Hall *et al.* 2001, Fan 2011), South Africa (Lorentzen and Barnes 2004, Kruss and Lorentzen 2009, Lorentzen 2009) and to a limited extent developing countries in Latin America and elsewhere.[15]

However, despite its explanatory potential, the application of the framework to developing countries is complicated by what Arocena and Sutz (2000) argue are normative tendencies that confer a national innovation system as continually self-correcting inefficient pathways toward the advancement and maturing of high-tech sectors and industries. The authors stress that whereas the framework for national innovation systems was initially developed as an ex-post concept and descriptive tool to explain economic development based on differences in innovative and technical performance between countries in the global North, it was now put forward as an ex-ante concept and prescriptive tool for guiding innovation policy in countries in the global South faced with the task of economic development and catch-up in the world economy (see also Bell and Pavitt 1993, Lorentzen 2010, Delvenne and Thoreau 2012 for discussions of national innovation systems in the context of developing countries). While many developing countries certainly had advanced innovative capacities and excelled in various sectors and industries, Arocena and Sutz argue that these often operate informally in isolation to anything resembling the integrated system of actors, networks, and institutions as described by the national innovation systems concept (see also Furman and Hayes 2004, Metcalfe and Ramlogan 2008 for critical discussions on the applicability of the national innovation systems concept in developing countries).

It is true that most analyses of developing countries tend to fall back on the narrow view of national innovation systems and mainly focus on technology-based manufacturing and high-tech industries, emphasising science-driven innovation based on R&D activities and STI relationships (e.g. Hong 2008, Eom and Lee 2010, Kang and Park 2012). However, this is not surprising considering that the framework was originally designed to explain differences in innovative and technical performance between developed countries, where capabilities to implement and manage innovation and technological change typically already exist. Nevertheless, as explained by Lundvall (2007), the major part of developing countries are faced with an 'innovation paradox' in which

[15] See for instance Thailand (Intarakumnerd *et al.* 2002), Algeria (Saad and Zawdie 2005), Chile (Klerkx *et al.* 2015), Egypt (Attia 2015), Ecuador (Fernández and Gavilanes 2017), Indonesia (Lakitan 2013), Mexico (Solleiro and Castañón 2005), Argentina (Correa 1998), Israel (Breznitz 2005), Iran (Ghazinoory and Ghazinoori 2006), and Malaysia (Felker and Sundaram 2007).

investment and progress in science are not matched by innovation outcomes and economic performance.[16] The author goes on to argue that this ambiguity cannot be explained by the narrow view of the national innovation system, 'without a broad definition of the national innovation system encompassing individual, organizational and inter-organizational learning, it is impossible to establish the link from innovation to economic growth' (2007:3). Feinson too argues, 'successful economic and industrial development is intimately linked to a nation's capacity to acquire, absorb and disseminate modern technologies. Whereas in developed economies the innovation system serves the role of maintaining or improving an already established level of competitiveness and growth, developing countries are faced with the task of catching-up' (2003:18). While a dichotomy between the global North and South is too simple and crude, Altenburg suggests that innovation systems in developing countries do differ from their more mature counterparts in developed countries: 'they need to cater for different needs; they build on institutional frameworks that tend to be much less formalised, and rules that are less enforceable; and the key agents as well as the incentives that determine their behaviour tend to be very distinct' (2009:33).

Consequently, when applying the national innovation systems framework in the context of developing countries, adjustments are required to incorporate the specific economic development challenges of the global South. First, linkages and networks between key actors and institutions are often weak or missing in developing countries, which may result in macro-economic and institutional instability, influencing the performance of national innovation systems (e.g. Hall *et al.* 2001, Allard *et al.* 2012). Second, inadequate financial and regulatory systems may result in volatile business environments that impair the ability of the public and private sector to operate efficiently, resulting in substantial productivity differences (e.g. Crespi and Zuniga 2012). Third, developing countries suffer from relatively weaker knowledge bases, implying that firms and knowledge institutes need to access and use external knowledge. The importance that national innovation systems remain open and receptive to external knowledge linkages is, therefore, increasingly recognised in the literature (e.g. Fu *et al.* 2011, Pietrobelli and Rabellotti 2011). Fourth, science, technology and innovation policy is often not coordinated and aligned with national development agendas and focus on strengthening the internal dynamics of national innovation systems, while paying limited attention to the role of external knowledge linkages (Chaminade and Padilla-Pérez 2017). Combined, the framework for national innovation systems as originally devised appears rather static and less suited to incorporate the particular economic development challenges faced

[16] See also Cirera and Maloney who elaborates, 'the innovation 'paradox' arises from the coexistence of great potential gains form Schumpeterian catch-up in developing countries with low innovation investment by firms, and the surprising lack of governments in increasing these investments by several orders of magnitude' (2017:60). The authors argue that for countries farther from the innovation frontier, the potential gains from catch-up increase but the lack of complementary capacities to manage innovation and technological change leave this potential unrealised.

by developing countries (see for instance Lundvall *et al.* 2009, Bartels *et al.* 2012, Chaminade *et al.* 2012). *Contrary to developed countries, where advanced innovative capabilities typically already exist, a key priority for developing countries, facing a wide array of economies development challenges, is to support the creation and accumulation of capabilities to manage innovation and technological change.* As will be explained in the following chapters, the creation and accumulation of capabilities needed to manage innovation and technological change involve different modes of learning and forms of knowledge; that is, interactive learning and capacity building processes influenced by national innovation systems, which in developing countries are often fragmented and still in formation.

2.3.5 Evolutionary perspective of national innovation systems

National innovation systems in the context of developing countries are often portrayed from an evolutionary perspective, where some system components are in place but where the linkages between these appear fragmented and still in formation (see for instance Chaminade and Vang 2008, Lundvall *et al.* 2009). According to Chaminade and Padilla-Pérez (2014), adopting an evolutionary perspective of national innovation systems in developing countries allows for a better understanding of the market and systemic failures that should be given priority at any moment in time. Ideal types of national innovation systems range from emergent and fragmented to mature systems, which can be associated with different levels of economic development and catching-up (see Table 3 for schematic presentation of ideal types of national innovation systems).

Table 3 Ideal types of national innovation systems

	Emergent systems:	Fragmented systems:	Mature systems:
Main objective	Technology adoption	Technology adoption/creation	Technology creation
Features and characteristics	Missing or weak institutional linkages result in socio-economic environments, characterised by a high degree of informality, corruption, and limited access to basic infrastructure, creating strong institutional voids that impair the ability of the public and private sector to operate.	Weak institutional frameworks result in socio-economic environments characterised by inadequate financial and regulatory systems, creating volatile business environments that impede innovation 'ecosystems' and the development and formation of science-industry linkages.	Strong institutional frameworks characterised by well-functioning patent laws, strong intellectual property rights, and good infrastructure, providing a stable, predictable, and enabling environment for innovation and favourable conditions for healthy entrepreneurial climates.
Technological capabilities	Low to medium levels of technological capabilities	Medium to high levels of technological capabilities	High to world-leading levels of technological capabilities
Countries	Low and middle-income group (e.g. Indonesia, Bolivia, Morocco, Vietnam, Ghana)	Middle-income group (e.g. Brazil, China, India, South Africa, Thailand)	High-income group (e.g. Chile, Israel Singapore, South Korea, Taiwan)

Adapted from Chaminade and Padilla-Pérez (2017) and Chaminade et al. (2018)

It is important to clarify here that the categorisation of national innovation systems is based on ideal types, which describes the common features of groups of developing countries: 'any scheme of this sort can be misleading if it is interpreted in a linear way, as a sequential model with one unique ideal development path. Far from that, adopting an evolutionary perspective implies that each innovation system is unique and there is not one single ideal type of innovation systems that all countries need to strive for nor one single path of development' (ibid 2014:10).

Contrary to *mature innovation systems*, which are characterised by macro-economic stability, strong regulatory frameworks, advanced technological capabilities, and enabling environments for innovation, *fragmented innovation systems* are found in the majority of developing countries. These innovation systems are characterised by two speeds or facets, where highly innovative clusters exist side by side with under-developed industries with relatively lower technological capabilities. Following Chaminade and Padilla-Pérez (2017), this makes policy formulation and implementation particularly challenging, since general policies targeting capability building or the attraction of technology-related foreign direct investment need to be combined with innovation policies tailored to the specific needs of the most advanced industries and sectors. In other words, both technology adaptation and technology creation are the central policy objectives in fragmented innovation systems. Previous studies in Asia show similarities across Singapore, South Korea, and Taiwan, where governments have successfully combined both supply-side and demand-side measures in the gradual move from fragmented to mature innovation systems, implementing industrial strategies that effectively balanced protectionism of key indigenous industries with different degrees of system openness – allowing these industries to adopt, exploit, and improve upon technology and organisational practices from developed countries and, in particular, those of Europe, Japan, and the United States. These policy measures, among other things, included intervention in key industries and sectors, strong government support for entrepreneurship and technology incubation programmes, along with carefully crafted government R&D programmes designed to support reverse engineering of foreign technology and patent protection (e.g. Lee and Von Tunzelmann 2005, Yim and Kim 2005, Tsai *et al.* 2009, Eom and Lee 2010, Wonglimpiyarat 2010, Hung and Whittington 2011, Kang and Park 2012, Wang *et al.* 2012, Jung and Mah 2013).

Similarly, middle-income countries such as China, India and Brazil have over the past decades emerged as global economic powers following consecutive government policies toward economic liberalisation and different degrees of system openness. Although the actual policies followed by these countries differed somewhat due to historical and national contexts, the strategies employed for catching-up purposes were very similar. These included attracting foreign trade and foreign direct investment, opening up of national industries to global competition, and supporting private enterprise and entrepreneurial activity (e.g. Fan 2011, Godinho and Ferreira 2012). Matthews (2009) and Fu and Zhang (2011) argue that the policies in these countries were reminiscent of the catch-up strategies employed earlier by Japan and the newly industrialised countries of East-Asia.

For instance, in the case of China, such policies included programmes and incentives for the adoption of foreign manufacturing technology, the gradual decentralisation of national R&D efforts from government research institutes to commercial enterprises, the encouragement of partnerships between domestic and foreign companies, and the establishment of numerous economic zones and science and technology parks, which over time became increasingly populated by multinational corporations (e.g. Gu and Lundvall 2006, Chen and Kenney 2007, Motohashi and Yun 2007, Wu 2007, Hu and Jefferson 2008, Tang and Hussler 2011, Zou and Zhao 2014).

India was able to capitalise on its historically strong science and engineering base and already burgeoning national industries in aerospace, computer electronics, and pharmaceuticals to develop a world-class, globally oriented information and communications technology industry and to become an emerging leader in medical equipment, biotechnology, and renewable energy (e.g. Aggarwal 2001, Hall *et al.* 2001, Parthasarathy and Aoyama 2006, Basant and Chandra 2007, Chaminade and Vang 2008, Mathews 2009, Fan 2011, Sharma *et al.* 2012, Burhan *et al.* 2017).

Compared to China and India, the Brazilian innovation system was characterised by a relatively weaker education system that produced a labour force whose skills were largely inadequate toward the widespread absorption and improvement of foreign technology (e.g. Franco *et al.* 2011, Suzigan and Albuquerque 2011). Consecutive Brazilian governments followed an industrial strategy that focused on encouraging foreign direct investments, particularly policies that made it easier for multinational corporations to set up and operate subsidiaries in the country. However, the operations of multinational corporations in Brazil were almost exclusively production oriented and remained so due to the low-skilled workforce. This is also the main reason that Viotti (2002) argues that national innovation systems as a framework is inappropriate, as technology creation, based on science-driven innovation, R&D, and STI relationships, are rarely the objectives of developing countries. Rather, the author proposed the concept of national learning systems, which were limited to the adoption of technology developed elsewhere. This depiction of national learning systems in developing countries, passively confined to the absorption of externally created knowledge, is misleading and has been vigorously challenged (see for instance Lorentzen 2010).

Emergent innovation systems are typically found in low and lower-middle income countries. These innovation systems appear fragmented and in the early stages of formation but interaction between the individual system components can still be traced. Here, some system components are present, but these often suffer from low technological capabilities, weak inter-organisational linkages, and socio-economic environments characterised by a high degree of informality, limited access to finance and basic infrastructure, poor business climates, weak institutions, and shortages of skilled labour (Lundvall *et al.* 2009). For instance, Lall and Pietrobelli (2005) studied national innovation systems in Ghana, Uganda, Kenya, Tanzania, and Zimbabwe, noting that in these countries, some institutions seemed potentially better positioned than others to support the STI relationships, R&D efforts, and science-based modes of learning. However, the authors go on to conclude that these countries 'generally lack the facilities (physical and human) to provide meaningful support to industrial enterprise … they have no means of assessing the technological needs of industrial enterprise or of diffusing to them the few technologies they have created' (ibid:334). Relatedly, Hall (2005) examined the efforts of a number of Sub-Saharan African countries to develop their own indigenous industries in agriculture and biotechnology. While pointing to some success in institution building, specifically in establishing linkages between national knowledge institutes and universities in the global North, the author points to substantial market and systemic failures. In particular, the lack of effective science-industry linkages, and absence of active government feedback mechanisms impede the formation of innovation capabilities and the development of technologically advanced industries and sectors.

To summarise. it is evident that national innovation systems in developing countries are characterised by highly heterogeneous economic structures and are more diverse and inferior in their ability to develop and diffuse scientific and technological knowledge compared to developed countries, which have developed mature innovation systems and more advanced capabilities to manage innovation and technological change. At the same time, however, it follows that in a constantly evolving context, emergent and fragmented innovation systems may develop into mature systems, while mature systems over time can turn in to dysfunctional and fragmented innovation systems (Chaminade *et al.* 2018). Based on this evolutionary perspective, the definition of national innovation systems adopted in this thesis is adapted from by Lundvall *et al.* (2009).

Box 2 Nation innovation system *(working definition)*

National innovation systems are open and evolving systems that encompass networks within and between actors, institutions, and socio-economic infrastructures, which determine the rate and direction of innovation, interactive learning, and capability building processes derived from the interplay between the STI and DUI learning modes.

This working definition draws on three key features. First, it specifies that the direction of innovation, interactive learning processes, and capacity building efforts reflect the attributes of the system components and the network relationships between these. This starting point is important for developing countries because it opens up the possibility of influencing development pathways so that the rate of innovation and capability building is high. But equally important, the notion of evolving innovation systems infers that developing countries do not necessarily have to follow the catch-up model of developed countries but can explore new and different directions of innovation along more sustainable development pathways, thus opening up qualitatively different segments of the innovation frontier. This point is important! As explained by Sutz (2019): 'if being 'developed' implies that the problems of environmental unsustainability and growing inequality are solved, 'developed countries' do not exist. Development as catching-up with the highly industrialised counted becomes meaningless in normative terms – besides being unfeasible in practical terms' (see also Dutrénit and Sutz 2014).[17] For instance, in the context of climate change, it is evident that developed countries carry the major part of historic responsibilities, whereas developing economies will indisputably take on significant costs as a result of their geographic location as well as their economic, social, and environmental conditions. At the same time, developing countries going through various stages of industrialisation are increasingly contributing to exacerbate existing societal and environmental challenges, and it is critical that these economies are not locked-in the same technological trajectories of developed countries but transition to sustainable and environmentally benign alternatives (Berkhout *et al.* 2009).

Second, this definition specifies that innovation capability formation of actors and organisations comprising the innovation system is a fundamental precondition for directional innovation and a strategic orientation of national innovation systems. Or to put it another way, to address contemporary societal challenges of the type of the SDGs, the creation and accumulation of capabilities needed to pursue innovation in new and different directions are an essential and necessary outcome of interactive learning and capacity building efforts.

Third, following Jensen *et al.* (2007), innovation processes and capacity building efforts do not result science-based learning and formal processes of R&D alone, but equally from tacit and experience-based knowledge and learning. Therefore, the working definition in this thesis is based on the broader view of national innovation systems adopted by Lundvall, where interactive learning is understood to derive from the balance and complementarity between the science, technology and innovation (STI) and doing, using and interacting (DUI) modes of learning.

[17] Catching-up is often (mis)understood to suggests one single pathway with a clearly defined innovation frontier. The notion of the innovation frontier tends to be associated with a specific trajectory (towards the same end-point) as that previously followed by innovation leaders. However, as argued by Figueiredo, 'in reality, the process of innovation and technological change cannot be represented using the analogy of a race along a fixed track, because of the possibility of successful overtaking by latecomers moving in new directions, and of the emergence of radical discontinuities that open up opportunities for them' (2010:1093). Relatedly, Lim and Lee (2001) identify three modes of catch-up, showing that latecomers do not follow a linear path but may skip some stages or even create new paths as they approach the innovation frontier. Hence, rather than a specific end-point, the innovation frontier is considered to be a fluid area or horizon to be explored. Therefore, in this research, the notion of 'catching-up' reflects a narrowing of the gap between developed and developing countries in terms of the capabilities of actors and organisations comprising national innovation systems to undertake innovative activities, or in other words, closing the gap to the innovation frontier.

Based on the above review, it is argued that the core of the systems of innovation approach – the national innovation systems concept – is mainly directed at optimising the innovation system to fulfil national economic policy objectives such as growth, jobs, and competitiveness but largely fails to guide processes of transformative change towards a broader range of desired societal objectives. Furthermore, although the concept has moved away from macro-level interpretations to an emphasis on specific system components and processes, the framework lacks explanatory power at the micro-level. Comparison of national innovation systems based on econometric analysis drawn from statistics and surveys has long been used to clarify the determinants and dynamics influencing the success or failure of innovation (see for instance Arundel *et al.* 2007, Fagerberg and Srholec 2008, van Beers *et al.* 2008, Sternberg and Arndt 2009, Guan and Chen 2012, Pinto and Santos Pereira 2013). However, innovation systems scholars and policymakers cannot easily derive policy recommendations from the comparative analysis of national innovation systems because context specificities make it difficult to 'translate' experiences from one system to another. In particular, the lack of useful and reliable science, technology and innovation indicators that allow for monitoring and comparison of national innovation systems presents a difficulty for effective policy formulation and implementation.[18] Arguably, much of this has to do with the legacy of evolutionary economics, which is mainly concerned with macro-level development in order to grasp the path dependencies and long-term trajectories of technological change. This has led to a strong emphasis on science-industry linkages but has weakened the depth of investigation of how different actors and organisations create and accumulate the capabilities needed to pursue new and different directions of innovation and how these interactive learning processes are conditioned and influenced by national innovation systems.

2.4 Refining the systems of innovation approach – emerging challenges and opportunities

A central premise of this thesis is that the systems of innovation approach needs to be conceptually refined to adequately address societal challenges of the type of the SDGs. This section draws out emerging challenges and opportunities for innovation systems research and suggests three lines of inquiry that may help refine the national innovation systems concept. It is suggested that a better understanding of the research themes outlined below may contribute to the development of a more integrative policy framework that incorporates directionality and a strategic orientation of innovation systems to legitimise policy interventions in processes of transformative change to address contemporary societal and environmental challenges.

[18] For instance, as argued by Edquist *et al.* (2018), standardised indicator-based benchmarking exercises, such as the European Union scoreboards, lead to over simplistic rankings and policy recommendations that were previously underpinned by a more systemic understanding of innovation (see also Grupp and Schubert 2010 for a discussion on the limitations of science, technology and innovation indicators).

A first proposition of the thesis is that the creation and accumulation of capabilities needed to pursue innovation in new and different directions along more sustainable development pathways are necessary prerequisites for implementing the SDGs. Notwithstanding the explanatory power of the national innovation systems concept, there is a poor understanding of how different actors and organisations, particularly in the context of developing countries, orchestrate processes of interactive learning needed to effectively manage innovation and technological change and how national innovation systems influence these learning processes. In particular, there is a need to understand better the intra-organisational dimension concerning the relationship between science and engineering and how latecomer firms balance processes of interactive learning derived from the interplay between STI and DUI modes of learning.[19]

Second, it is increasingly acknowledged that innovation processes work across interrelated spatial scales and may be organised globally (Coenen *et al.* 2012). The analytical limit of innovation systems studies to particular spatial scales seems increasingly less appropriate (e.g. Martin 2016, Weber and Truffer 2017). To be clear, it is not suggested here that space does not matter for innovation or that interactive learning processes cannot be regarded as a place-based phenomenon. The rich stream of research on innovation systems that has emerged over the last decades has firmly established that networks of actors and institutions situated around local knowledge bases intensify interactive learning and innovation. Nevertheless, it is argued here that much research has been overly preoccupied with studying discrete spatial scales as determinants of innovation, rather than probing the network relationships that run through and across innovation systems.

Third, the frame of reference for innovation has changed over the last decade and with it, the requirements for conceptual approaches that underpin innovation policy. The discourse about addressing contemporary societal and environmental challenges is increasingly framed in terms of transformative innovation policy that not only contributes to economic growth objectives but also addresses a broader range of societal and environmental objectives (Diercks *et al.* 2019). With a few notable exceptions (see for instance Schlaile *et al.* 2017, Schot and Steinmueller 2018), most innovation systems scholars agree that systems of innovation continue to provide a useful heuristic but that it needs to be conceptually refined in order to legitimise policy interventions for transformative change to address the nature and complexity of interconnected and systemic societal challenges. However, despite growing research in this field, there is a poor understanding of the possible refinements to the systems of innovation approach that are needed to design innovation policy for transformative change.

[19] On this matter, for instance, in the context of clean energy industries, Figueiredo concludes that future studies could 'investigate how policies and the wider innovation system shape (or are shaped by) firms' capability accumulation processes' (2017:430).

3. Methodology and research design

The writing of a thesis requires reflection of the methodology and methods used in the research. The chapters in the empirical part of the thesis have different theoretical foci but are guided by the same analytical and methodological considerations. It is therefore relevant in this part of the thesis to provide reflections on the philosophy of science that forms the relationship between knowledge and the process by which it is developed. This research is grounded in post-positivism (logical empiricism) and is based on abductive reasoning. In broad terms, the thesis is exploratory and qualitative and makes use of multiple methods of data collection, including interviews, participant observations, and documentary evidence. Each of the three empirical chapters contains more detailed information on the specific methods used to collect and interpret data. The point here is not to reiterate but rather to complement the methods descriptions in the empirical chapters, so as to provide a fuller picture. The rest of the chapter is organised as follows. Section 1 explains the purpose of the research. Section 2 clarifies the ontological and epistemological position of the research. Section 3 introduces the systematic combining approach followed in the thesis and elaborates on the matching between theory and the empirical world and the corresponding direction and redirection of the research. Section 4 presents the case study design, while section 5 describes the data collection methods employed in the thesis. Section 6 explains the analytical procedures of the research. This is followed by an account of the methodological challenges of the research as well as the strategies used to address these limitations.

3.1 Research purpose

As described in the previous chapters, the purpose of the research is to conceptually refine the systems of innovation approach, and in particular revise the national innovation systems concept, thereby taking steps towards the development of a more integrative innovation policy framework that incorporates directionality and a strategic orientation of innovation systems to address contemporary societal challenges of the type of the SDGs. The rationale and purpose of the research thus in some ways resembles what Alvesson and Sandberg (2011) refer to as 'problematisation', here understood as a methodology for identifying and challenging assumptions that underlie existing theories. This is similar to Kilduff, who asserts that 'the route to good theory leads not through gaps in the literature, but through an engagement with problems in the world' (2006:252). Before introducing the systematic combining approach used in the thesis to answer the overall research question and meet the underlying research objectives, the next subsection considers the epistemological and ontological position of the research.

3.2 Ontological, epistemological, and methodological considerations

Research is about the creation of true and objective knowledge following a chosen methodology. From the gathering of data and information, it is possible to acquire a reasonably adequate basis for empirically grounded conclusions, which can then serve as the basis for generalisation and theory-building. In order to consider the suitability of the chosen methodology of the thesis, it is therefore necessary to clarify the ontological and epistemological position of the research and to commit to a certain view of what one believes is possible and what is not possible in reality.

In general, there exist two overarching philosophies of science regarding what we can know about the world and how we can know it: positivism and relativism (also referred to as objectivism and subjectivism). These two extreme positions can be considered as opposite ends of the spectrum in terms of their conception of reality. According to positivism, the aim of research is to create objective knowledge, whereas relativists argue that knowledge is socially constructed and therefore subjective to the researcher. This research is grounded in post-positivism, which has direct implications for the way the study is conducted. It implies that the observer of social phenomena can never be fully independent of the research topic being studied. As explained by Silverman, 'how we frame a research problem will inevitably reflect a commitment (explicit or implicit) to a particular model of how the world works' (2013:11). On the one hand, the epistemology adopted in the research is rooted in social constructivism, which concentrates on, 'the ways that people make sense of the world especially through sharing their experiences with others via the medium of language. … we should therefore try to understand and explain why people have different experiences, rather than search for external causes and fundamental laws to explain behaviour' (Easterby-Smith *et al.* 2008:58). Therefore, research that captures the complexity of social phenomena with the aim of theory-building is not of key importance in social constructivism: '[rather] the challenge here is to enter the social world of our research subjects and understand their world from their point of view' (Saunders *et al.* 2009:107). In this respect, reality is not objective to the researcher but is socially constructed and given meaning by people. On the other hand, the epistemological position taken in the research resembles that of critical realism, which denotes that it is possible to develop objective knowledge, although the possibilities for this are somewhat limited because we all have subjective experiences of the world (Bhaskar 1975). Critical realists assert there exists a reality independent of our thinking about it, but our consciousness and knowledge about this reality are theory-laden and fallible. As argued by Danermark *et al.*, 'while it is evident that reality exists and is what it is, independently of our knowledge of it, it is also evident that the kind of knowledge that is produced depends on what problems we have and what questions we ask in relation to the world around us' (2002:26).

Combined, the epistemological assumption adopted in the research; therefore, also to a certain degree resembles that of pragmatism, where it becomes easier to think of philosophy of science as a continuum rather than opposite positions. The research questions and objectives thereby guide and influence the epistemology adhered to in the research and underscore the pragmatist view that 'it is perfectly fine to work with both philosophies' (Saunders 2009:110).

Whereas epistemology is concerned with how knowledge is obtained, or truth is verified, ontology is about how the world is constructed. It follows that the ontological position of the research influences the choice of methods used to collect and interpret data. Put differently, 'to commit oneself to an epistemology is also to commit oneself to a position on a range of ontological issues' (Hay 2007:117). This research is built on the presupposition that 'social phenomena are created from the perceptions and consequent actions of social actors. What is more, this is a continual process in that through the process of social interaction these social phenomena are in a constant state of revision' (Saunders 2009:108). The social phenomena under study thereby exist as conceptual constructs qua science and the way in which questions are asked. Data and theory triangulation were used as a research strategy, whereby various perspectives of the same phenomena were considered by applying different theoretical lenses and analysing multiple data sources (Meijer *et al.* 2002). Nevertheless, due to the research methodology employed, and in particular the systematic combining approach used to analyse and interpret data and information (which enabled 'equivocal evidence' or 'biased views' on the part of the researcher), this inevitably impacted the direction and redirection of the research (Yin 2018).

3.3 Systematic combining – an abductive approach to case research

This research follows the systematic combining approach proposed by Dubois and Gadde (2002). According to the authors, 'systematic combining is a process where theoretical framework, empirical fieldwork, and case analysis evolve simultaneously' (ibid:554). In general, systematic combining can be understood as the combination of inductive and deductive approaches, an abductive method of reasoning derived from going back and forth between theory and the empirical world. An inductive approach proceeds from a number of single cases and infers that a connection that can be observed across these is probable and generally valid. Induction typically relies on grounded theory and can be described as the gathering and use of data and information to systematically generate theories (Strauss and Corbin 1990). Deduction, on the other hand, has its starting point in theory and is concerned with developing propositions from current theory. This is typically done by, 'deducing a hypothesis, a testable proposition about the relationship between two or more concepts or variables from theory' (Saunders 2009:117).

Abduction infers that the research work and analytical framework are successively reoriented when confronted with the empirical world. New empirical findings may suggest that theoretical influences are added to the research, while at the same time, the development of conceptual constructs influences the direction of the study. Hence, as explained by Alvesson and Sköldberg, 'the method has some characteristics of both induction and deduction, but it is very important to keep in mind that abduction neither formally nor informally is any simple 'mix' of these nor can it be reduced to these; it adds new, specific elements. During the process, the empirical area of application is successively developed, and the theory is also adjusted and refined. In its focus on underlying patterns, abduction also differs advantageously from the two other, shallower models of explanation. The difference is, in other words, that it includes understanding as well' (2002:4).

A core proposition in systematic combining is the intertwined nature of different research activities. In this regard, the conventional view of the research process, consisting of a number of planned consecutive phases does not reflect the potential advantages of systematic combining. In systematic combining, the research departs from a preliminary understanding and builds on a number of articulated preconceptions, but the analytical framework is continually developed and refined based on what is discovered through the empirical findings. As suggested by Dubois and Gadde, 'the main objective of any research is to confront theory with the empirical world. What we argue above is that in systematic combining this confrontation is more or less continuous throughout the research process' (2002:553). The intertwined nature of research activities implies that the analytical framework is continually expanded and revised as the work proceeds: 'the evolving framework directs the search for empirical data. Empirical observations might result in the identification of unanticipated yet related issues that may be further explored in interviews or by other means of data collection. This might bring about a further need to redirect the current theoretical framework through expansion or change of the theoretical model' (ibid:553).

In this way, systematic combining is suitable for the further development or refinement of existing theories, 'we stress *theory development*, rather than *theory generation.* Systematic combining builds more on refinement of existing theories than on inventing new ones … in studies relying on abduction, the original framework is successively modified, partly as a result of unanticipated empirical findings, but also of theoretical insights gained during the process. This approach creates fruitful cross-fertilization where new combinations are developed through a mixture of established theoretical models and new concepts derived from the confrontation with reality' (ibid:559). The next subsection proceeds by unpacking the systematic combining approach in terms of two central processes concerning the matching between theory and the empirical world and the corresponding direction and redirection of the research (see Figure 2).

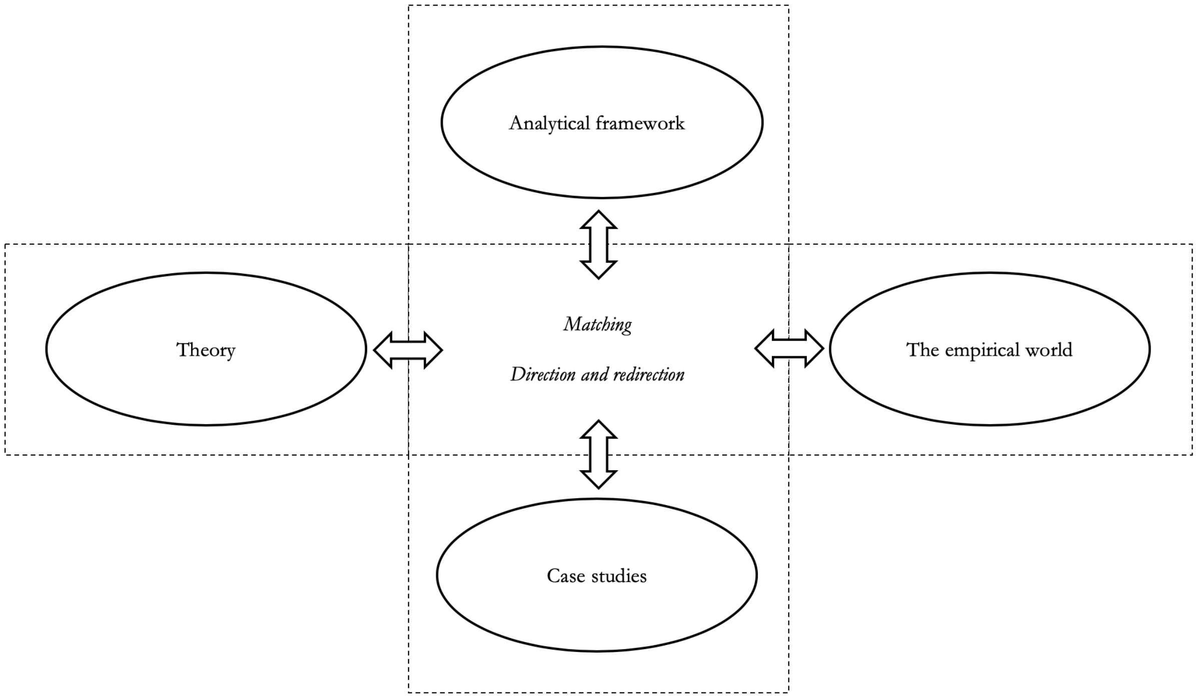

Figure 2 Systematic combining – an abductive approach to case research

3.3.1 Matching – alternating between theory and the empirical world

Matching concerns the non-linear process of alternating between theory and the empirical world. The method can be adapted for use in inductive or deductive analysis or a combination of the two; that is, one can apply pre-existing theoretical constructs deductively and then revise theory with inductive aspects, or one can use an inductive approach to identify themes in the data before using theory deductively to help further explain these themes. According to Dubois and Gadde (2002), a combined approach is appropriate when previous research undertaken is scarce and theoretical relationships are difficult to construct. Considering the exploratory nature of the research, the continuous interplay between the empirical findings and existing theory on innovation systems is used to enhance understanding and inform the study as the work proceeds. This abductive method of reasoning allows theoretical influences or constructs to emerge from the analysis itself: 'the objective is to discover new things – other valuables and other relationships. … The researcher should not be unnecessarily constrained by having to adhere to previously developed theory. Theory is important, but it is developed over time. Hence, the 'need' for theory is created in the process' (ibid:559). Consequently, in parallel to the collection of empirical data for the thesis, the search for theoretical influences complementary to innovation systems concepts was ongoing, guided by the premise that the empirical observations and the framework did not match. For this effort, theoretical concepts and influences were added to the analytical framework that could help explain some of the interdependencies between what could be empirically observed

(Timmermans and Tavory 2012). To this end, Glaser (1978) points to the importance of the fit between theory and reality and argues that data should not be forced to fit preconceived or pre-existent categories, asserting instead that categories and themes are to be developed from data, which can then help explain what can be empirically observed. In a similar vein, Dubois and Gadde stress the parallel development of the analytical framework, since categorising without such a theoretical platform necessarily adds less to our understanding. To summarise, the purposeful application of matching entails rigorous planning but is argued to result in a more structured research process. Besides, matching is a flexible tool, which can be adapted for use with different qualitative approaches that aim to identify commonalities and differences before concentrating on the relationships between the different parts of the data, thereby seeking to draw out explanatory conclusions around emerging categories and themes.

3.3.2 Direction and redirection of the research – the evolving framework

The basic features needed to achieve the matching between theory and the empirical world concerns the direction and redirection of the analytical framework based upon a broadened understanding of the research. As previously explained, the approach in systematic combining is not to identify theory completely beforehand but rather to develop theoretical concepts in parallel with the empirical data collection. It follows that the way the boundaries of the analytical framework are expanded is of great importance as it influences how empirical data will be collected and what will be found. In this regard, Miles and Huberman distinguish between two ideal types of frameworks, one which can be classified as being tight and pre-structured, the other as loose and emergent. Each type has its strengths and weaknesses. Too much prior structuring of the framework will, 'blind the researcher to important features in the case or cause misreading of local informants' perceptions' (1994:16). Hence, on the one hand, the disadvantage of an excessively pre-structured framework is that it might screen off potentially important features. On the other hand, a loosely structured framework might lead to overload due to the unrestricted collection of data. According to Dubois and Gadde (2002), the distinction between two ideal types of analytical frameworks proposed by Miles and Huberman does not apply in systematic combining. Rather, the authors assert the framework should be tight but at the same time evolving. This implies that the analytical framework should be focused while it should be allowed to change based on the new empirical findings. In this regard, Blumer (1954) suggests that theoretical concepts should be used rationally to create a reference and to function as guidelines when entering the empirical world. Similarly, Bryman (2015) argues that theoretical concepts provide the researcher with a set of general guidelines; that is, the successive refinement of theoretical concepts implies that they constitute the input as well as the output of abductive research. Hence, the reason the analytical framework evolves during the research is that empirical observations inspire changes in theory and vice versa. As described by Van Maanen *et al.,* 'abductive reasoning is considered a means of assigning primacy to the empirical world but in the service of theorizing' (2007:1149).

3.4 Developing propositions from case study research

Following Dubois and Gadde (2002), the interaction between social phenomena and their context is best understood through case studies. This rationale builds among others on Eisenhardt who argues that case study research provides a unique means of developing theory by utilising insights of contemporary phenomena in their real-life contexts: 'there are times when little is known about a phenomenon, current perspectives seem inadequate because they have little empirical substantiation, or they conflict with each other or common sense. … in these situations, theory building from case study research is particularly appropriate because theory building from case studies does not rely on previous literature or prior empirical evidence' (1989:548). Yin defines case study research as an 'empirical method that investigates a contemporary phenomenon in depth and within its real-world context, especially when the boundaries between phenomenon and context may not be clearly evident' (2018:15). Considering the exploratory purpose of the research, a multiple case study design was chosen as the appropriate method of research. Importantly, however, although the empirical chapters comprise three sets of cases studies, these do not follow the replication logic as described by Yin (2018). As explained by Dubois and Gadde, 'the movement toward deep structures is problematic to achieve in linear and replicative research where research issues, frameworks and case boundaries are formulated at the outset of the study. Discovery of deep structures is more likely to occur in the continuous movements back and forth, involving matching and redirection as in systematic combining and other approaches aiming at context-specific explanations' (2014:1283). It follows that the systematic combining approach followed in the thesis obviates the replication logic typically used in multiple case study research. To the contrary, this research is based on one of the core principles of critical realism that explanation depends on identifying causal mechanisms rather than on the number of times something has happened. Hence, the cases studied in this research are treated as revelatory cases. Seeking out unique or revelatory cases is one way that helps ensure that the research provides empirical evidence with which to consider new conceptual constructs or validate proposed concerns. In other words, revelatory cases are considered useful, when these are based on common criteria that help to develop new understandings based on the conceptual propositions that underpin the research. Therefore, three separate but interlinked cases that form the empirical part of the thesis are studied to verify and validate various aspects of the analytical framework. In practice, this means that although the research objectives are similar and focus on innovation, interactive learning, and capacity building processes in developing countries, the cases studies are not identical but have been contextualised and adapted to the individual circumstances.

3.4.1 Case selection

Three propositions on how to revise the framework for national innovation systems and refine the systems of innovation approach to incorporate directionality and a strategic orientation of innovation systems towards a broader range of societal objectives were outlined in section 2.4. Following the systematic combining approach, these three research themes – *capabilities, networks, and directionality* – are explored through multiple case studies. The first research proposition on the creation and accumulation of capabilities needed to pursue innovation in new and different directions along more sustainable development pathways are examined in a subsidiary of the global biotechnology company, Novozymes, operating in the Brazilian bioethanol sector. Novozymes was a forerunner in connecting its innovation activities with the SDGs, which today are deeply embedded in its strategy 'Partnering for Impact'. Novozymes has deliberately (re)prioritised its technology pipeline and partnership opportunities to embrace and align with the 2030 Agenda for Sustainable Development (Novozymes 2015). As explained by Head of Corporate Sustainability at Novozymes, Claus Stig Pedersen, 'by understanding the Global Goals – the global challenges – we can target our innovation to meet the needs of the present and future generations' (Novozymes 2016). Drawing on the literature on technological capabilities, the first case study explores how changes to the relationship between the STI and DUI modes of learning influenced innovation capability building in the subsidiary of Novozymes over a 10-year period and how these interactive learning processes were conditioned by the Brazilian innovation system.

Building on the preceding chapter and considering the changing geography of innovation, the second proposition of the thesis is that interactive learning processes are increasingly enacted through the formation of global innovation networks spanning national innovation systems. Drawing on the strategic management literature and recent insights from economic geography, chapter 5 develops an understanding of how the formation of global innovation networks works to enhance processes of interactive learning in national innovation systems and further proposes a model for how international technology cooperation may complement innovation capability accumulation in developing countries. A multiple case study compares two prominent initiatives for international technology cooperation in the context of climate change: (1) Climate Technology Centre and Network is the main innovation intermediary of the United Nations Framework

Convention on Climate Change and (2) International Energy Agency Technology Collaboration Programmes is a key initiative for international technology cooperation outside of the convention.

Shaped by the emerging policy paradigm for transformative change described in chapter 1, and based on the understanding derived from the two previous chapters, the third proposition of the thesis is that current rationales for innovation policy are insufficient to address contemporary societal challenges of the type of the SDGs. Chapter 6 takes steps towards the development of a new innovation policy framework, which integrates insights from the system innovation perspective and opens up the systems of innovation approach to incorporate directionality and strategic orientation of national innovation systems towards addressing not only economic policy objectives but also a broader range of societal and environmental objectives. The compatibility of the integrated innovation policy framework is assessed with reference to two policy initiatives: (1) United Nations Conference on Trade and Development Science, Technology and Innovation Policy Review programme is one of the main innovation-oriented capacity building initiatives of the UN and (2) United Nations Technology Facilitation Mechanism was established as part of the 2030 Agenda for Sustainable Development to legitimise policy interventions in processes of transformative change to address the SDGs.

3.5 Data collection

Case study research benefits from multiple sources of evidence, which allow for 'converging lines of inquiry' (Yin 2018). Triangulation involves using data collected through different methods, which enables the researcher to corroborate empirical findings across different data sets and thereby reduce the impact of potential biases that can exist in a single study (Patton 1990). Huberman and Miles express this as 'self-consciously setting out to collect and double check findings' (1994:438). However, verification and validation of data and information is not the main issue in systematic combining. Rather, multiple sources of evidence may contribute to revealing aspects unknown to the researcher that may lead to the discovery of new dimensions of the research problem. Hence, the emphasis in this research is on exploration and theory development based on the patterns that emerge from the empirical data collection (Dubois and Gadde 2002). According to Eisenhardt, this is one of the hallmarks of building theory from case studies: 'creative insights often arise from the juxtaposition of contradictory or paradoxical evidence. … the process of reconciling these contradictions forces individuals to reframe perceptions into a new gestalt' (1989:546). Combined, the three sets of cases studied in the thesis draw on interviews, participant observations, and documentary evidence. These different data collection methods are described in more detail in the following subsections.

3.5.1 Interviews

The primary data source in this research originates from semi-structured interviews. In general, interviews are considered to be the mainstay of qualitative research and can provide the tool to gain access to social constructions of meaning and value that may otherwise be difficult to examine. The critical realist position followed in the thesis asserts that case study research must be theoretically informed (see for instance Danermark *et al.* 2002). Following this line of reasoning, the semi-structured interview is considered a suitable data collection method as this is based on a theoretically informed and thematically organised interview guide that contains central and open-ended questions. Moreover, the semi-structured interview is context-sensitive and allows the researcher to prepare the interview guide based on the specific context and background of the interviewee. Hence, the theoretically informed interview guide, on the one hand, and its open and flexible character, on the other, ensure the back and forth between the concrete and the abstract. Put differently, the practitioners and policymakers interviewed for the research provided tacit knowledge about the layer of the actual, while the researcher attempted to systematically interpret and understand this data and incorporate it into concepts, thereby coming closer to the layer of the real (Bhaskar 1975). This is in line with the abductive method of reasoning guiding the research to not only make an empirical contribution but also to put forward theory development.

The thesis draws on more than 50 semi-structured interviews collected during fieldwork in Brazil in 2016 and during a research stay with the UNEP DTU Partnership in Denmark in 2017 and 2018.[20] The majority of interviews were made face-to-face, but in a few cases, interviews were conducted over the telephone. The knowledge gained from the interviews were decisive for the total number of interviews conducted for each case study. Hence, the process of abduction ended when additional interviews did not lead to new insights but rather confirmed what was already known. Most of the interviews lasted between 60 – 90 minutes and were digitally recorded in agreement with the interviewees. As several of the interviews contained sensitive information that captured personal opinions and perceptions of the interviewee, complete anonymity and confidentiality were assured. Consequently, only the position and organisation of the interviewees are indicated in connection with direct quotations. Some interviewees, acting as the representatives of their respective organisations, declined to be recorded, so this data is only available in the form of interview notes. For reliability, each interviewee was given the option to verify the written case description (Mosley 2012). This procedure was applied both to inform the interviewees about the state of the research but also to ensure the validity of the empirical findings (Sarantakos 2005).

[20] UNEP DTU Partnership is organisationally part of the Department of Technology, Management, and Economics at the Technical University of Denmark. Located in the UN-City in Copenhagen, UNEP DTU Partnership is a collaborating centre of UN Environment Programme (UNEP) and is a leading international research and advisory institution on energy, climate, and sustainable development.

3.5.2 Participant observations

Participant observation is a data collection method, which allows the researcher to learn about the phenomena under study in its natural setting through observation and participation in activities (Kawulich 2005). Marshall and Rossman define participant observation as 'the systematic description of events, behaviours, and artefacts in the social setting chosen for study' (1989:79). DeWalt and DeWalt argue that 'the goal for design of research using participant observation as a method is to develop a holistic understanding of the phenomena under study that is as objective and accurate as possible given the limitations of the method' (2002:92). On this matter, Angrosino and DePerez (2000) advocate a structured process to maximise the efficiency of participant observations, minimise researcher bias, and facilitate replication or verification by others, all of which make the empirical findings more objective. The authors suggest that participant observations may be used as a way to increase the validity of case studies but that the quality of the observations depends upon the skill of the researcher to observe, document, and interpret what has been observed. This is similar to Schensul *et al.* who argue that participant observations are filtered through interpretive frames and that 'the most accurate observations are shaped by formative theoretical frameworks and scrupulous attention to detail' (1999:95). Therefore, it is essential to make accurate observation field notes without imposing preconceived categories and theoretical perspectives but allow these to emerge from the analysis. Nevertheless, it is evident that research has more validity when participant observations are triangulated and combined with other data collection methods, such as interviews or other more quantitative methods.

Participant observations during fieldwork and at various events and meetings presented an opportunity to engage informally with practitioners and policymakers, thereby gaining insights into relevant issues and debates. For instance, participation in political conferences, such as the 22nd and 23rd Conference of the Parties of the United Nations Framework Convention on Climate Change in 2016 and 2017, and the United Nations Technology Facilitation Mechanism 'Second Annual Multi-stakeholder Forum on Science, Technology and Innovation for the Sustainable Development Goals' in 2018 allowed to check the expression and definitions of terms that participants use and facilitated informal discussions with policymakers during side events and exhibits. Moreover, during fieldwork in Brazil in 2016, participant observations in the R&D department and its research laboratories allowed an immersion in the innovation climate of Novozymes and an insider view of its daily activities. This provided a unique opportunity to witness the organisational context in which innovation happens. Combined, this allowed for a more complete and comprehensive understanding of the research problem that would have been unobtainable from passive observations and other methods of data collection.

3.5.3 Documentary evidence

Documentary evidence including strategic and organisational documents, such as mission statements, enabling frameworks, decisions texts, white papers, annual reports, fact sheets, industry studies, competitive reports, presentations, and newsletters, were used in combination with the interviews and participant observations as a means of triangulation (Denzin 1970). As discussed by Merriam, 'documents of all types can help the researcher uncover meaning, develop understanding, and discover insights relevant to the research problem' (1988:118). In the context of this research, documents often proved to be the most effective means of gathering data, especially when (past) events could not be observed or when interviewees had forgotten specific details. Furthermore, documentary evidence often suggested additional questions that needed to be asked and situations that needed to be observed as part of the research. Finally, as described above, documents were used deliberately as a way to triangulate findings or corroborate empirical evidence from the multiple sources of data. Put another way, if the empirical evidence from different sources proved contradictory rather than corroboratory, the researcher investigated further (see also the discussion on data and theory triangulation in Yin 2018).

3.6 Analytical procedures

Similar to other qualitative analytical procedures, such as ethnography or phenomenology, systematic combining involves primary data to be collected and interpreted to extract new meanings and understandings. To make sense of the vast amount of data collected for the research, an attempt was made to systemically organise and structure the data into categories and themes. Coding was performed to classify the primary data sets (interviews and participant observations) so that these could be systematically compared with secondary data (Saldana 2009). This involved a comprehensive process, where elements of content analysis and thematic analysis were applied. Content analysis refers to the process of organising data and information into categories related to the research questions being explored in the thesis, whereas thematic analysis relates to pattern matching within the data, where emerging themes become the categories for further analysis (e.g. Denzin and Lincoln 2005, Fereday and Muir-Cochrane 2006, Saunders *et al.* 2009).

During the early stages of research, different categories of data were clustered around similar categories and emerging research themes. The preliminary coding process required the ability to strike a balance between reducing the data, on the one hand, and retaining the original meaning on the other. While the initial categories were vague and imprecise, developing these were considered useful to start the process of abstraction of the primary data; that is, moving towards the general rather than the specific or anecdotal, and it furthermore provided a structure for which to systematically reduce the data. Gradually, characteristics of and differences between the categories were identified, which led to the interrogation of theoretical concepts relevant for the research, either prior concepts or new ones emerging from the data (Gale *et al.* 2013).

The categorisation of primary data was considered useful for the subsequent thematic analysis, where it became important to compare and contrast data by different themes. The development of themes is a common feature of qualitative data analysis that involves the systematic search for patterns to generate full descriptions capable of shedding light on the phenomenon under investigation. Themes were identified and developed by interrogating data categories through comparison within and across the cases. Each research theme – *capabilities, networks, and directionality* – comprised separate tables in which interview segments and field notes from participant observations could be inserted. During the later stages of the research, these tables were carefully analysed and categorised within the specific research themes, which allowed intermediate interpretations to be distilled and preliminary conclusions to be drawn.

3.6.1 Methodological limitations and challenges

The issue of how to assess quality in qualitative research has always been subject to intense debate, but ensuring rigour and transparency are necessary and vital components of any piece of research (e.g. Lincoln 1995, Seale 1999, Morse *et al.* 2002). Having declared the methodology used in this thesis to the principles of abduction, and systematic combining (based on multiple case studies) as the main method of research, this subsection proceeds to discuss the methodological limitations and challenges of the research. The methodology is assessed first in terms of validity; that is, the degree to which the study measures what it claims or purports to be measuring, and second, with respect to reliability that concerns the extent to which the research can be replicated.

Acknowledging that case studies have their drawbacks and limitations, it can be argued from a critical realist perspective that case study research provides scientific value (Flyvbjerg 2006, Eisenhardt and Graebner 2007). As opposed to positivism, which strives for generalisability, case study research aims for thick descriptions of social phenomena and detailed accounts of events as a way of producing reliable results (Hyett *et al.* 2014). The quantity of observations as such is not decisive for arriving at new meanings and understandings. Rather, as Sayer explains, 'what causes something to happen has nothing to do with the number of times we have observed it happening. Explanation depends instead on identifying causal mechanisms and how they work, and discovering if they have been activated and under what conditions' (2000:14). Therefore, the notion that case studies lack statistical reliability does not present an obstacle to this research. The intention is not to test casual relationships or a predefined hypothesis, which would have required a different methodology. In critical realism, the stratification of the real, the actual, and the empirical imply that truth is conditional and can be revised (Bhaskar 1975). Hence, following Kvale (1996), when generalisations are made, these are in the form of 'analytical generalisations'.

Interpretive research implies that it is not always possible to achieve validity by following the principles of cause and effect, thereby establishing causality rather than correlation of social phenomena. In systematic combining, as in other forms of qualitative inquiry, such as grounded theory, the researcher is the primary instrument of data collection and relies on skills as well as intuition to filter data through an interpretive lens. Accepting that nature is partially based on the meaning we ascribe to it inspires a study of meaning-making that reveals the underlying assumptions, values, and ideas of the researcher. For instance, as argued by Huberman and Miles, 'researchers have their own understandings, their own convictions, their own conceptual orientations ... they will undeniably be affected by what they hear and observe in the field' (1994:8). Although the data collection methods employed were directed towards the search for data in line with the framework for national innovation systems, an integral part of systematic combining is to allow these activities to be complemented by efforts aiming at discovery. For instance, participant observations during meetings and other events beyond the control of the researcher contributed to data collection that would not have happened otherwise. These observations generated new questions on which further interviews were based. The knowledge and insights that resulted from unanticipated data contributed to the further development of the analytical framework and triggered the search for complementary theoretical concepts. Moreover, the author was involved in collecting data and writing the manuscript for Diercks *et al.* (2019), which inevitably influenced the direction and redirection of the research.[21] To put it another way, validity and truth are highly context-dependent but herein also lies the strength of social science to discover interests and values through deliberation, interpretation, and reflection (Trochim 2002). The views and values of the researcher must, therefore, be recognised as influencing the research process and can at best be managed by applying appropriate standards. Validity was achieved by using different sources of data, establishing a chain of evidence, and pursuing verification of the written cases. Furthermore, the researcher kept a research diary and updated the log, taking field jottings and descriptive notes during the interviews when digital recordings were not an option (Emerson *et al.* 2001). Finally, the validity of interpretations was accounted for through extensive supervisor sessions as well as presentations at conferences, seminars, and workshops.

[21] In parallel to the writing of this thesis, early drafts of the manuscript for Diercks *et al.* (2019) were circulated between the three authors and presented at the International Sustainability Transitions conference in 2015, the SPRU: 50th Anniversary Conference in 2016, and the Eu-SPRI Annual Conference in 2017. The comparison of alternative explanations and critical discussions between the three authors on the different features of transformative innovation policy had a significant influence on the direction and redirection of the research carried out in this thesis.

4. Explaining interactive learning as determinant for innovation capability building: Firm-level evidence from the Brazilian innovation system

The process of how industrial firms create sustainable competitive advantages based on innovative capabilities has been a key topic of research over the past decades. The broad and multifaceted literature has generated a substantial body of theoretical frameworks and empirical evidence across a wide variety of industries and countries. In this field, empirical studies on firms in developing countries have mainly focused on analysing the building of a knowledge base and the gradual progression through different levels of capability to effectively manage innovation and technological change to develop new products, processes, and services (e.g. Dutrénit 2000, Figueiredo 2001). This strand of literature has traditionally considered that initially imitative firms (commonly referred to as latecomers) over time acquire and build up a minimum base of knowledge, on the basis of which new and increasingly complex technological activities can be carried out.[22] This process of accumulating deeper and broader stocks of knowledge to manage innovation and technological change in latecomer firms is generally referred to as innovation capability building (see for instance Lall 1992, Bell and Pavitt 1995, Figueiredo 2002).

Innovation studies have long argued that the internal organisation of capabilities to implement innovative activities in latecomer firms is conditional on internal learning and external knowledge. Concerning this matter, Kim (1997) demonstrates how the interaction between external knowledge and internal learning is organised in successive cycles of deliberate and continuous learning activities. The capability to manage internal learning in the firm is in turn derived from its prior knowledge base and capacity to absorb external knowledge (Cohen & Levinthal 1990). Consequently, external knowledge may complement learning in the creation of innovative capabilities in the latecomer firm and may contribute to deepening those capabilities through the subsequent use of technology, which goes beyond merely routine operations, to enable a series of cumulative innovation and further technological change (Bell 2009). Despite these rich insights, it remains poorly understood exactly how external knowledge is combined with internal learning and in what way changes to this dynamic relate to the attainment of specific levels of innovative capability over time. For instance, this knowledge gap is highlighted in the recent literature review by Bell and Figueiredo (2012:69): 'we know little about the relative importance of different learning mechanisms and even less about whether and how this varies as firms deepen their innovative capabilities' (see also Hansen and Lema 2019).

[22] Following Bell and Figueiredo, latecomer firms can be described as initially imitative firms characterised by their 'historically determined, rather than strategically chosen, position of late entrant, reflecting the late industrialisation of their economies (2012:16).

To enhance our understanding on the internal organisation of capabilities as to effectively manage innovation and technological change, this chapter goes beyond the traditional focus on internally and externally mediated learning mechanisms and is concerned with how latecomer firms orchestrate processes of interactive learning derived from the interplay between science and engineering in order to create and accumulate innovation capabilities. Building on the seminal contribution of Jensen *et al.* (2007), *interactive learning* is understood to derive from the balance between two distinct but complementary modes of learning: science, technology and innovation (STI) and doing, using and interacting (DUI). The strategic management literature has generated relevant insights into the STI and DUI modes of learning and how this relationship influences firm-level innovative performance. Nevertheless, most studies are based on large samples of firms and cross-sectional design and econometric analysis drawn from statistics and surveys. Such level of aggregation provides only a static picture of the current situation and little evidence on how the relationship between the two learning modes evolves over time. This does not permit to capture how firms use the STI and DUI modes of learning to implement innovative activities from a micro-level perspective. Furthermore, most studies have been undertaken in the context of developed countries, where capabilities to implement innovative activities already exist. With a few notable exceptions (see for instance Chen *et al.* 2011, Egbetokun 2015), there is a dearth of empirical evidence on the relationship between the STI and DUI modes of learning in latecomer firms in developing countries and how this contributes to the creation and accumulation of capabilities needed to manage innovation and technological change. Therefore, this chapter is guided by the following research question: how do changes to the relationship between the STI and DUI modes of learning influence innovation capability building in latecomer firms? The remainder of the chapter is organised as follows. Sections 1 and 2 present an understanding of interactive learning as derived from the balance between the STI and DUI modes of learning and innovation. Section 3 proposes a taxonomy of research and experimental development (R&D) activities in latecomer firms. Section 4 presents the empirical setting while the methodology is outlined in section 5. Sections 6 and 7 reports a qualitative case study on innovation capability building for a Brazilian subsidiary of the global biotechnology company, Novozymes. Section 8 discusses management implications for innovation capability accumulation in latecomer firms.

4.1 Division between science and engineering: a cognitive model of innovation

The cognitive model of innovation developed by Nightingale (1998) is useful to illustrate the interplay between science and engineering in the firm. The model breaks down engineering into a stylised sequence of steps, starting with a general belief based on prior knowledge and practical experience, which is used to recognise similarities between a variety of technical problems. Based on intuition and this tacit understanding of how technology works, a new creative idea is formed. This is followed by practical experimentation, in which new configurations are tested through processes of trial and error. Results are fed back through an iterative learning process, leading to the continuous modification of the initial configuration, until an acceptable outcome is achieved.

Science complements engineering and is used to test if new configurations work as originally intended. This involves methods of extrapolation, whereby data are fitted into pre-existing patterns and used to recognise and generate new patterns. Put differently; science is used to understand how changing the starting conditions in engineering effects the end result. As described by Nightingale: 'when patterns are subjected to tests and found to pass they are reinforced and when they fail they are rearticulated, which itself may entail the further testing of underlying assumptions' (1998:695). Hence, science entails the ability to interpret abstract patterns of nature to reduce the amount of information needed to understand the world. Consequently, science does not contribute directly to technological change – the argument of Nightingale leads to the direction argument in the innovation cycle – but indirectly to test unknown configurations. In this way, an unknown solution to a technical problem is conceptualised by extrapolating a similar configuration for a previously solved problem (Nelson 2004). Innovation and technological change involve iteratively moving from known to unknown configurations – an interactive learning process characterised by the interplay between science and engineering.

To explore how the interplay between science and engineering influences the process of building innovative capabilities in latecomer firms, this chapter draws on the concept of knowledge base as originally developed by Nelson and Winter (1982). The knowledge base is broadly defined here as comprising the 'set of information inputs, knowledge and capabilities that inventors draw on when looking for innovative solutions' (Dosi 1988:1126). Furthermore, technology is understood as 'configurations that work', indicating that its functioning depends on various interconnected elements (Rip and Kemp 1998). In this way, the knowledge base can be understood as comprising the universe of technical possibilities from a given set of configurations known to the firm. Configurations can be categorised in technological systems according to their level of complexity in a 'technological hierarchy' (Disco *et al.* 1992).[23] Complexity shapes the configuration of technology at lower hierarchical levels, as change in one constituent part of the technological system entails that other elements have to change as well (Stankiewicz 2000).

[23] Technological systems have a narrow and broad meaning (Bergek *et al.* 2008). In the former, the technological system is applied to a technology and is understood in the sense of a knowledge field. The broader definition (commonly referred to as a technological innovation system) delineates the technological system in terms of the network of agents interacting in the generation, diffusion, and utilisation of technology (Carlsson and Stankiewicz 1991). In this chapter, the technological system is narrowly defined and is understood in terms of a specific knowledge field.

Drawing on the cognitive model innovation, the diversification of the knowledge base is therefore understood to involve the test of new configurations through science and the modification of existing ones through engineering. Following Nelson and Winter (1977), the accumulation of the knowledge base over time is path dependent and bounded by technological regimes. This infers a powerful search heuristic, which implies that innovation and technological change progress somewhat blindly in certain directions while ignoring others, an evolutionary impetus analogous to that of technological paradigms (Dosi 1982). Thus, latecomer firms can be understood to organise and manage processes of interactive learning, and in turn the balance between the STI and DUI modes of learning and innovation, in relation to the prior knowledge base of a given technological system. As explained by Aslesen *et al.,* 'the two main innovation modes of STI and DUI are thus related to different forms of learning and technological development. The different forms of learning are a result of their different dominating knowledge bases which will be decisive for type of knowledge used' (2012:392). The cumulative nature of the knowledge base can, in this way, be thought of as forming a 'technological tradition' that guides firms by providing certain pathways for the resolution of technical problems (Nightingale 1998).

4.2 Interactive learning – the interplay between science and engineering

The capabilities needed to manage innovation and technological change is understood here to result from the interplay of science and engineering – an interactive learning process characterised by the balance between the two distinct but complementary modes of learning: STI and DUI (Jensen *et al.* 2007). Drawing on a latent class analysis of 1,643 Danish firms, the authors demonstrate that the combined use of STI and DUI modes of learning has more positive effects on innovative performance than does the use of either mode in isolation. Importantly, though, the two learning modes do not necessarily operate in harmony with each other and, as emphasised by Jensen *et al.*, 'it is a major task for knowledge management to make strong versions of the two modes work together in promoting knowledge creation and innovation' (2007:690).

Subsequent studies have scrutinised the relationship between the two modes of learning and how it influences firm-level innovative performance. Irrespective of contextual circumstances, there is general agreement that the combined use of STI and DUI modes of learning has more positive effects on firm-level innovative performance than does the use of either mode in isolation. For instance, studies within the European context and based on surveys of large numbers of firms and quantitative analysis have supported the argument of Jensen *et al.* (2007), such as those in Norway (Aslesen *et al.* 2012), Sweden (Isaksen and Nilsson 2013), and Portugal (Nunes and Lopes 2015). Using a qualitative design based on case studies in Norway, Isaksen and Karlsen (2010) reach similar conclusions. In the Norwegian context, Fitjar and Rodriguez-Pose (2013), based on a survey of 1,604 firms, support the argument that both modes of learning matter for innovative performance. Another set of studies from different contexts have reached varied conclusions. Drawing on a sample of 4,696 firms in Spain, Gonzales-Pernía *et al.* (2015) find that while product innovation benefits more from a combination of STI and DUI modes of learning, process innovations are more related to the DUI mode of learning. Drawing on a firm-level panel of 3,165 firms in Spain, Parrilli and Heras (2016) find the STI mode of learning is associated more with technological innovation, whereas the DUI mode influences non-technological innovation. These conclusions are supported by Thomä (2017), which based on a survey of 6,851 firms in Germany finds that firms with less knowledge intensity exploit their competitive advantages through the DUI mode of learning and firms seek to offset their limited in-house R&D through collaborations with external partners. Drawing on a sample of 209 firms in China, Chen *et al.* (2011) find that greater scope and depth of openness for both the STI and DUI modes of learning improve firm-level innovative performance. Similarly, based on an econometric analysis of 170 firms in Nigeria, Egbetokun (2015) finds that both modes of learning are positively associated with firm-level innovative activities. The individual features of the two learning modes are discussed in more detail in the following subsections.

4.2.1 Experience-based learning based on doing, using and interacting relationships

Engineering is characterised by the separation of design and production. The accumulation of a minimum base of knowledge allow the firm to hypothetically design configurations using various analytical devices and diagnostic tools. As a result, technical performance characteristics and critical constraints can be predicted and measured somewhat accurately and precisely. The modification of configurations is reflected in the top-down approach typical of design and engineering activities; broad features of technology are initially outlined and used as specification for more detailed designs. Nonetheless, the interdependency between configurations at interrelated hierarchical levels often makes the technological system analytically intractable. However, interpreting the actual mechanisms and causal relations supporting working configurations is often not of primary importance in engineering. As argued by Nelson, 'much of engineering design practice involves solutions to problems that professional engineers have learned 'work' without any particularly understanding of why' (2004:458). The learning and experience derived from engineering have much in common with 'know-how' in the taxonomy by Lundvall and Johnson (1994). What matters is whether configurations work, not whether the underlying mechanisms and causal relations are fully understood.

As the knowledge base is diversified over time, practitioners may start to concern themselves with exploring the functionality of technology. Hence, a common activity in engineering is experimental development related to incremental improvement of practical technical problems encountered in the interaction between users and producers (von Hippel 2005). This corresponds with the notion of the 'operational principle' of how technology works (Vincenti 1990). A practical technical problem presents practitioners with a function that a technology ought to fulfil, while the operational principle defines the basic way in which the technology can be configured to fulfil that function. This is what Layton aptly described as 'the purposive adaptation of means to reach a preconceived end' (1974:35). The initial outcome of engineering is typically the development of a technical model or blueprint, which serve as the codification of a proposed set of configurations. A critical next step is then the application of the technical model into a working prototype. Despite this stylised sequence of steps, technology is not developed purely based on knowledge of how it works, as detailed knowledge of why it works as it does is needed to identify its structure and function. Thus, science complements engineering in diversifying the knowledge base within which practitioners make informed decisions with regard to the configuration of technology.

4.2.2 Science-based learning based on science, technology and innovation relationships

The knowledge base of the firm tends to accumulate and become more diversified over time. Arising from specific adaptations to contextual circumstances, the knowledge base initially comprises a highly complex and heterogeneous set of information inputs, knowledge, and capabilities (Dosi 1998). As described above, the diversification of the knowledge base involves, among other things, testing new configurations through science. Compared to traditional engineering, in which such discoveries are somewhat accidental and serendipitous, the deliberate testing of new configurations presupposes the prevalence of an analytical knowledge base in the firm (Asheim and Coenen 2005). Science allows abstract patterns of nature to be understood, which leads to increased insight into why technology works as it does.[24] As argued by Jensen *et al.*, 'results of scientific research are not directly useful for technological advance. Rather, the contribution of science is usually more indirect ... it is understanding that pertains to particular artefacts and techniques which distinguishes technology from science. The STI-mode of innovation most obviously refers to the way firms use and further develop this body of science-like understanding in the context of their innovative activities' (2007:683).

[24] To reiterate, science is not directly used in technological development, but it does play a vital indirect role in innovation and technological change. As described by Nightingale, 'when science is used to explain, it moves from concrete phenomena to abstracted patterns in its behaviour, leaving behind all the symmetry breaking information, that makes any situation specific. But when it is used for prediction this extra information is needed and is not contained in the original laws. This difference between explanation and prediction by science is important in understanding the differences between science and technology' (1998:233).

Referring again to the knowledge taxonomy of Lundvall and Johnson (1994), this STI mode of learning has much in common with 'know-why' with a focus on understanding and interpretation. Hence, science complements engineering in different ways. First, science is used to unravel the complex relationship between structure and function of configurations in technological systems. This allows for an understanding of why technology works as it does and how changes to its configuration affect functionality and performance. Second, science is used to perform approximate tests based on generic properties, such as stability, reliability, and transparency, in order to ensure that configurations meet certain predetermined design criteria (aspects like size, weight, durability, etc.) before being applied empirically. This reduces uncertainty and the number of experimental dead-ends. Third, the reflective character of science is used to interpret abstract patterns in nature, so as to recognise technical problems in novel situations and extrapolate possible solutions from previously solved problems.

4.2.3 Combing the STI and DUI modes of learning and innovation: a framework for interactive learning

Previous studies in the field of strategic management find that the STI mode of learning revolves around the production of codified and explicit knowledge, emphasising the use of scientific methods and principles with a focus on understanding and interpretation. The DUI mode of learning, on the other hand, relates more to user-producer interaction, in which practical technical problem-solving based on tacit and experience-based knowledge play important roles. To analyse the internal organisation of capabilities in latecomer firms as to manage the interplay between science and engineering, and in turn the balance between the STI and DUI modes of learning, interactive learning is operationalised as two intertwined processes: appropriation and application.

This division builds on a rich body of literature on technological learning in latecomer firms, which has developed over the last decades. Bell and Figueiredo (2012) revise the listings of various learning mechanisms related to innovative capabilities, which have previously been identified, and propose two general categories of learning: first, that which involves acquiring and assimilating knowledge from external sources; and second, that involving knowledge and experience derived from learning internal to the firm (building on, among others, Bell 1984, Bell and Pavitt 1993, Hobday 1995, Kim 1997, Dutrénit 2000, Figueiredo 2001, Figueiredo 2003, Ariffin and Figueiredo 2004). Examples of the former include collaborations with universities and research institutes, hiring experienced managers and staff, and codified knowledge acquisition through strategic alliances or other forms of contractual arrangements. Examples of the latter include formalised and planned activities that take place in the firm by engaging in continuous improvements of products, processes, and equipment. For instance, experimentation may give rise to learning-by-changing through the modification of configurations, particularly if this builds on practical experience. Another example is trial and error learning that takes place through practical technical problem-solving. Likewise, different training programmes including course-based and on-the-job training, may provide learning opportunities in latecomer firms (e.g. Hansen and Ockwell 2014).

The comprehensive categorisation of Bell and Figueiredo (2012) clarifies the relationship between external and internal learning mechanisms and focuses on the deliberate processes by which knowledge and experience are acquired and built up by latecomer firms in the creation and accumulation of innovative capabilities. However, the conventional distinction between internally and externally mediated learning seems less suitable to explain how the interplay between science and engineering, and in turn changes to the relationship between the STI and DUI modes learning, influence the process of innovation capability building in latecomer firms. Therefore, in this study, the two modes of learning are operationalised for the purpose of explaining how and in what way changes to this relationship influenced the process of innovation capability building in the context of the Brazilian subsidiary of Novozymes over a 10-year period.

Appropriation relates mainly to the STI mode of learning, in which science-based learning is gained from experimentation and testing of configurations in the technological system. Stankiewicz describes the appropriation of knowledge as follows: 'in order to be retrievable, transmittable and operationally accessible the unwieldy corpus of technical knowledge has to be structured and whenever possible reduced to generic formulas. This creates an internal meta-technological research agenda based on the reflection on the 'state-of-the-art' rather than determined by specific practical needs of the moment' (1992:32). Application, on the other hand, relates mainly to the DUI mode of learning, in which experience-based learning is gained from engineering activities and practical technical problem-solving in concrete situations. Kline refers to the application of knowledge as follows: 'we construct and operate … systems based on prior experiences, and we innovate in them by open loop feedback. That is, we look at the system and ask ourselves 'how can we do it better?' We then make some change, and see if our expectation of 'better' is fulfilled' (1995:69). As emphasised by Jensen *et al.* (2007), the interaction between the two modes of learning is complex and inherently difficult to separate in practice. The authors propose measuring the STI mode of learning through three standard measures, namely, firm-level R&D expenditures, educational level of employees, and external research collaboration, whereas the DUI mode of learning takes place through various kinds of internal training and development, involvement in practical technical problem-solving, and user-producer interaction. Drawing on the extant literature and empirical grounded observations, six specific learning mechanisms are assessed in the context of Novozymes in the Brazilian bioethanol industry (see Table 4).

Table 4 Specific learning mechanisms assessed in Novozymes

Science-based learning mechanisms based on science, technology and innovation (STI) relationships:
1. Experimentation and testing of configurations in the technological system serve as a way to appropriate knowledge and lead to increased insight into why technology works as it does.
2. External research collaborations with relevant organisations, including universities and research institutes, provide a means to appropriate knowledge in the Brazilian innovation system.
3. Hiring experienced managers and scientists with the right competencies, technical skill set, and research experience present a way to appropriate knowledge and diversify the knowledge base.
Experience-based learning mechanisms based on doing, using and interacting (DUI) relationships:
4. Practical technical problem-solving through iterative processes of trial and error provides a means to learn from the application under different contextual conditions.
5. User-producer interaction with customers and suppliers in the Brazilian innovation system presents a way to learn from the application of knowledge in concrete situations.
6. Internal training and development provide a means to apply and pass on knowledge through skill development, supervision, and direct instruction.

Author's own elaboration based on, among others, Stankiewicz (1992), Kline (1995), Jensen et al. (2007), Bell and Figueiredo 2012, Hansen and Ockwell (2014)

Based on the framework of Figueiredo (2003), processes of appropriation and application can be disaggregated into individual learning mechanisms and assessed based on three key features: (1) variety, (2) intensity, (3) functioning. *Variety* relates to the range of learning mechanisms that Novozymes engaged with over time to appropriate and apply knowledge in bioethanol production. The variety of learning mechanisms is classified here as absent, emergent, or present. *Intensity* relates to the extent to which the variety of learning mechanisms was pursued over time. Intensity is here classified as either intermittent or continuous. *Functioning* refers to how the variety of learning mechanisms functioned over time. Individual learning mechanisms work in different ways and some may deteriorate or become obsolete over time. Functioning is here classified as poor, moderate, or good. A framework for interactive learning is suggested in Table 5.

Table 5 Framework for interactive learning in Novozymes

	Features of learning mechanisms		
	Variety: absent, emergent, or present	Intensity: intermittent or continuous	Functioning: poor, moderate or good
Science-based learning based on science, technology and innovation (STI) relationships	A variety of science-based learning mechanisms is used to test new configurations to accumulate and diversify the knowledge base.	The extent to which science-based learning mechanisms are pursued leads to increased insight into why technology work as it does.	The way science-based learning mechanisms are organised and function over time influences the interplay between science and engineering.
Experience-based learning based on doing, using and interacting (DUI) relationships	A variety of experience-based learning mechanisms is used to solve practical technical problems encountered in concrete situations.	The extent to which experience-based learning mechanisms are pursued contributes to improve technical problem-solving.	The way experience-based learning mechanisms are organised and function over time influences the ability to solve technical problems.

Based on Nightingale (1998), Figueiredo (2003), and Jensen et al. (2007)

4.3 Levels of innovative capability in latecomer firms

The literature on firm-level technological capabilities has over the last decades developed various frameworks of classifying 'levels' or increasing 'depths' or 'degrees' of creative engagement with technology. This notion of gradual progression along a spectrum running from production capabilities for operating and maintaining technology towards innovative capabilities for managing and changing technology is well established. To this end, the important distinction between production and innovation capabilities of firms has provided a nuanced understanding of the notion of technological 'catch up' in developing countries (Bell and Pavitt 1993). The former is concerned with the technology used by latecomer firms in production and narrowing the gap between their production capabilities and those of latecomer firms operating close to or at the technological frontier. The latter refers to the capabilities with which latecomer firms manage and change technology where the gap to be closed is between copying and adopting existing technology on the one hand and improving and creating it on the other. These insights on intra-firm differentiation between production and innovation capabilities have helped move beyond the simplistic and controversial view that innovation and technological change in latecomer firms are confined to the imitation of existing technology. Different methods use varying terms and concepts, but all infer that different levels of capability lie behind the different types of innovative activity in the latecomer firm (see for instance Lall 1992, Bell and Pavitt 1995, Figueiredo 2002).[25] However, despite the rich stream of research that have emerged over the last decades, most empirical work have focused on the gradual progression from production capabilities into the lower levels of capability, whereas relatively few studies have explored the 'qualitative discontinuities' involved in the later stages of innovation capability building, when latecomer firms explore significantly different directions of innovation and technological change.[26]

There has been some empirical work on qualitative discontinuities in innovation capability building in the context of latecomer firms. In her study of a Mexican glass container manufacturer, Dutrénit (2000) was perhaps the first to demonstrate how the relationship between the technological and organisational dimensions in latecomer firms influences the transition towards operating at the innovation frontier. Exploring the experience of selected assembled product industries in Korea, Lim and Lee (2001) identify three modes of technological catch-up, showing that latecomers do not necessarily follow a linear path but may skip some stages or may even create

[25] These and later studies (including the present one) have drawn on what Bell and Figueiredo (2012) refer to as a 'revealed capability approach', which involves identifying levels of increasing novelty and significance in terms of innovative activity in the latecomer firm and then inferring that different capability levels underlie different types of innovative activities (see also Sutton 2012).

[26] Following Figueiredo (2011) who integrate insights from existing frameworks on technological capabilities and approaches to technological catch-up, 'qualitative discontinuities' are broadly defined here as shifts in the innovative capability building process that enables latecomer firms to pursue new directions of innovation and technological change along different technological trajectories from that already followed by the global leaders operating at or close to the innovation frontier.

new pathways as they approach the technological frontier. Similarly, with reference to Singaporean electronics and biotechnology firms, Amsden and Tschang (2003) observe a noticeable 'qualitative divide' in the objectives, activities, and outputs of R&D, when moving along the spectrum from advanced and exploratory development towards applied and basic research. Other studies have focussed more on the strategic issues related to innovation capability building in the transition from followers to leaders in innovation. For instance, Hobday *et al.* (2004) examine the different pathways of catch-up followed by Korean firms that involved competing based on low-cost product imitation or based on new product development and in-house R&D.

Combined, these studies provide relevant insights into the accumulation of capabilities needed to operate and maintain technology in production systems and those needed to accumulate deeper and broader stocks of knowledge to manage innovation and technological change. Nevertheless, the empirical evidence is mainly drawn from assembled products industries primarily in Asian countries and based on frameworks that interpret capability accumulation along existing technological trajectories.[27] These findings shed little light on the qualitative discontinuities involved in path-creating catching-up and how latecomers negotiate such shifts in the later stages of the capability building process. Subsequent studies have explored this issue. Figueiredo (2011) examines the speeds and dynamics related to discontinuous innovation capability accumulation in Brazilian natural resource-processing firms, following new technological trajectories in the pulp and paper industry. The qualitative discontinuities involved in the later stages of innovation capability building are also apparent in Chuang and Hobday (2013), who in their study explore the diversification of knowledge bases in Taiwanese electronics firms through the building of absorptive capacity involving three successive phases; from pre-entry and entry to innovation and diversification. Although this work provides empirical evidence on the upper levels of capability, these studies have largely overlooked the role that different sources of learning play in discontinuous innovation capability accumulation. This issue is studied in the recent contribution by Figueiredo and Cohen (2019), which explores the concept of path-creation technological catch-up in Brazil's forestry industry. This chapter seeks to extend previous research and is concerned with how interactive learning contributes to qualitative discontinuities in the later stages of innovation capability building. Specifically, this chapter is concerned with how and in what way changes to the relationship between the STI and DUI modes of learning influenced the gradual progression from intermediate to advanced innovative capabilities in Novozymes in Brazil (see Table 6 for a schematic presentation of technological capabilities in Novozymes).

[27] For instance, the gradual progression from production to innovation capabilities is often portrayed as the linear advance of latecomer firms from original equipment manufacturing (OEM) to original design manufacturing (ODM) and original brand manufacturing (OBM) (Hobday 1995).

Table 6 Levels of capability in industrial enzyme technology development

		Illustrative elements of technological capability in Novozymes:	
Innovative capabilities:	Level 5: World-leading	Capability to create new industrial enzymes technology, production processes, products, and equipment based on applied and basic research activities that are new to the world.	A substantial and varied body of internationally recognised R&D personnel with teams of highly specialised scientists, engineers, and related professional, working on cutting edge research at or close to the innovation frontier. These teams work across different functional areas and organisation units within the firm and outside the firm, conducting basic and applied research activities to develop new enzyme products and bioethanol process technologies, which lead to the improvement to pretreatment technologies and increases in the functionality and performance of enzyme products.
	Level 4: Advanced	Capability to implement complex modifications in industrial enzyme technology based on experimental development and applied research activities that are new to the market.	Substantial increase in scientists and engineers with PhD qualifications and specialised knowledge in different functional areas, working on applied research activities directed at developing new or improved enzyme products and process technologies; strategic partnering with key customers and suppliers, where highly specialised teams of engineers troubleshoot all parts of the pretreatment and hydrolysis stage, resulting in increasingly complex customer-specific solutions optimised to local market conditions and raw material characteristics.
	Level 3: Intermediate	Capability to implement complex modifications in industrial enzyme technology and production processes based on experimental development activities that are new to the firm.	Increased numbers of scientists and engineer, working informally on developing research methods, screening techniques, and accurate simulations that allow for experimental development activities, in which the generic properties of industrial enzymes are tested on biomass substrates, leading to an incipient understanding of the different stages in bioethanol production; partnering with local customers and suppliers, where engineers and other professionals work on practical technical problem-solving through iterative processes of trial and error; implementing advanced quality controls systems, following internal audits; ensuring continuous product surveillance and improvement to the safe handling of enzyme products.
	Level 2: Basic	Capability to implement relatively complex changes in industrial enzyme technology based on non-original experimentation, engineering, and design in line with global efficiency and quality standards.	Dedicated groups of engineers and qualified technicians, working on implementing minor adaptations and improvements to enzyme products, processes, and automation systems; incorporating quality controls to ensure that enzyme products are given optimal stability during storage and transportation and that production processes and procedures are up to standard with respect to health and safety standards; documenting that product, processes, and procedures are developed in compliance with national and international legislation.
Production capabilities:	Level 1: Advanced	Capability to implement operational activities based on the use of advanced enzyme technologies and production systems in line with company quality standards and procedures.	Teams of qualified technicians and well-trained operators, working on incorporating quality management into daily activities and routines; implementing systematic processes of storage, processing, and waste shipment; assuring that product and production processes are aligned with the requirements from local authorities, customers and suppliers.

Author's own elaboration based on, among others, Bell and Figueiredo (2012) and Figueiredo (2017)

To identify how and in what way changes to the relationship between the STI and DUI modes of learning influenced progression in the upper levels of innovative capabilities in Novozymes, a taxonomy of research and experimental development (R&D) activities is proposed. Conventional classification schemes typically rely on time or the calibre of the research personnel in the firm as objective criteria to distinguish between different categories of R&D activity. For instance, research activity is considered to lie at the basic end of the spectrum if the timeframe involved is longer than those of applied research and experimental development. Similarly, the educational level or occupation of employees often works as a proxy for research conducted in the firm. These features are helpful to distinguish between the two extremes – basic research on one hand and experimental development on the other – but do a poor job at differentiating the middle ground.

To differentiate more finely between the upper levels of innovative capability and between the different dimensions of capability in Novozymes, this chapter draws on the Frascati Manual, which categorises R&D activities undertaken in the firm to increase the stock of knowledge and to devise new applications for existing knowledge (OECD 2014). The proposed taxonomy differentiates between three qualitatively different types research activity: experimental development, applied research, and basic research. Experimental development relates to the application of existing knowledge directed towards producing new products, processes, or services. Applied research refers to an original investigation but with a specific practical aim or objective. Basic research is experimental or theoretical work to develop new knowledge but without any particular application. Ideally, a taxonomy of different types of R&D activity in the upper levels of innovative capability should match the relationship between the STI and DUI modes of learning, but there are caveats. Each type of R&D activity is not necessarily mutually exclusive as interlinkages and dependencies exist between them This iterative nature is one reason that categories of R&D activity at are not easily differentiated (Amsden and Tschang 2003). Nevertheless, in the context of this study, a stylised taxonomy that categorises qualitatively different activities of R&D is considered useful for identifying how changes to the relationship between the STI and DUI modes of learning influences the gradual progression from intermediate to advanced innovative capabilities in Novozymes.[28] The following elements are considered in the taxonomy of R&D activities: (1) search, (2) activity, (3) output (see Table 7). Search relates to the objectives of R&D, while activity relates to the set of attendant techniques and methods employed to achieve the search. Output relates to how the end results of R&D are put to use.

[28] This builds on Amsden and Chang (2003) who argue that experimental development remains largely in the domain of engineering and revolves around knowledge development tightly coupled with solving manufacturing and prototyping problems. The progression to applied and basic research enters the domain of science, involving increasingly demanding and technically more complex engineering and scientific methods of extrapolation of a known concept to an unknown end.

Table 7 Taxonomy of research and experimental development (R&D) activities in Novozymes

	Qualitatively different research activities categorised by increasing levels of innovative capability		
	Experimental development:	Applied research:	Basic research:
Search	Systematic search for suitable configurations based on practical experience and the prior knowledge base of Novozymes, which is directed at solving practical technical problems in concrete situations.	Original investigation deliberately undertaken to diversify the knowledge base of Novozymes by testing new configurations, which is directed at developing new or improving existing technologies.	Experimental or theoretical work is principally undertaken by Novozymes to discover the fundamental principles and modus operandi of new configurations with no particular application in view.
Activity	Modification of existing configurations are extrapolated and tested through iterative processes of trial and error for specific commercial application, based on the formulation of creative ideas.	Creative and systematic work is undertaken to determine possible uses for the output of basic research or new methods for achieving predetermined objectives by considering existing configurations.	Creative and systematic work is undertaken to understand the relationship between the structure and function of configurations with a view to formulate and test scientific hypotheses, theories, and laws.
Output	Results are subject to extrapolation and testing, leading to the application of modified configurations in the development of improved products, processes, and services.	Results are intended primarily to be valid for their application in the development of new or improved products, processes, and services by giving operational form to creative ideas.	Results are principally oriented and directed toward broader scientific fields of general interest and inquiry with the (possible) explicit goal of a range of possible future applications.

Based on Amsden and Tschang (2003) and OECD (2015)

4.4 Empirical setting: Bioethanol, Brazilian innovation system, and Novozymes

This section presents the empirical setting of the study. The first part describes the second-generation bioethanol production process. This is followed by a description of the Brazilian innovation system focussing on the bioethanol industry. The third part presents the history of Novozymes in Brazil and its bioenergy related activities.

4.4.1 Second-generation bioethanol production

Biomass represents a promising renewable energy opportunity that could provide an alternative to the use of fossil fuels. Biomass can be used as a source of energy, which can either be burned directly via combustion to produce heat and electricity or indirectly after converting it to various forms of liquid fuels, such as bioethanol and biodiesel. In this way, biomass utilisation not only reduces our dependence on fossil fuels but also impacts positively on many environmental issues and helps to minimise the net production of greenhouse gases (Goldemberg 2007). Focussing on bioethanol production, this revolves around the extraction of sugar monomers from biomass, which can be hydrolysed and fermented into ethanol. First-generation bioethanol production refers to concentrating and extracting sugar monomers from juice extracted from culms and subjecting the residual molasses to fermentation and distillation (Sánchez and Cardona 2008).[29] However, fermentation of the stored soluble sucrose fraction typically corresponds to only about one-third of the biomass, while residues and waste account for the remaining two-thirds. By degrading the structural component and extracting the soluble cellulose from the fibrous part of biomass waste and residues that are discarded from various industrial processes, such as agriculture (corn stover, sugarcane bagasse, straw, etc.) and forestry (sawmill and paper mill discards, etc.), it is possible to increase bioethanol production significantly. This process is referred to as second-generation bioethanol production and has the benefit of abundant and diverse forms of biomass.

Second-generation bioethanol avoids one of the major problems concerning first-generation bioethanol production, which sets up competition for feedstock with consumption purposes through direct and indirect land use. This attractive possibility has put second-generation bioethanol production at the forefront of the global sustainability agenda, and it is widely viewed as the next level of development for the bioethanol industry that could significantly reduce demand for fossil fuels in ways that first generation bioethanol production cannot (Leite *et al.* 2009). For instance, studies in Brazil have shown that if 50% of the bagasse generated from sugarcane

[29] A handful of crop species have been identified as productive feedstocks for use in first-generation bioethanol production including sugarcane, sugar beet, sorghum, maize miscanthus, switchgrass, poplar, and willow. The use of a given feedstock for bioethanol production primarily depends on the location in which that crop is produced. For instance, in temperate climates, poplar, willow, and switchgrasses are typically used as bioenergy crops whereas in subtropical climates sugarcane has the potential to be feedstock in bioethanol production (Khanna *et al.* 2009).

production were converted into bioethanol, this would represent improved production of 60% more litres of bioethanol per hectare (Soccol *et al.* 2010). However, although second-generation bioethanol production benefits from abundant and diverse forms of biomass residues and waste, it is harder to extract the sugar monomers and requires greater processing to make the carbohydrates available to the microorganisms used to produce ethanol.

Second-generation bioethanol production is divided into four general stages: (1) pretreatment, (2) hydrolysis, (3) fermentation, (4) distillation (see Figure 3). Efficient and cost-effective biomass conversion is highly dependent on a multidisciplinary approach to integrate the four production stages. The following subsections briefly describe the pretreatment and hydrolysis stages, where industrial enzymes are added to the feed. Pretreatment is a key step in biomass conversion. Biomass is composed of mutually entangled and chemically bonded carbohydrate polymers containing different sugar monomers (glucose and xylose) that are tightly bound to lignin. Biomass is inherently recalcitrant, and pretreatment is needed to liberate the cellulose from the lignin seal and its crystalline structure so as to render it accessible to hydrolysis and fermentation (Gámez *et al.* 2006).[30] Pretreatment of biomass is also needed to minimise the formation of degradation products because of their inhibitory effects on the subsequent hydrolysis and fermentation stages. The presence of inhibitors not only complicates but also increases the cost of second-generation bioethanol production due to the entailed detoxification step (Polizeli *et al.* 2017). Hence, to produce sugar molasses and bioethanol in high enough concentrations to minimise distillation costs, the process design must allow access of industrial enzymes to carbohydrates in order to efficiently hydrolyse the biomass as well as to provide a beneficial environment for the subsequent fermentation and distillation stages (Meyer *et al.* 2009).

Various methods have been developed for the pretreatment of biomass, which have different advantages and disadvantages depending on the feedstock in question (see for instance Hendriks and Zeeman 2009). In Brazil, steam explosion is a widely used method for fractionating biomass components into different process streams (Buckeridge and Souza 2017). It is a process where biomass is exposed to high-pressure steam under optimal conditions followed by quenching the reactor content to a pressure vessel. The result is a breakdown of the biomass structure and depolymerisation of cellulose and lignin through which the susceptibility of plant polysaccharides to enzymatic hydrolysis is improved (Hernández-Salas *et al.* 2009). Steam explosion provides lower capital investment than other pretreatment methods and has a relatively lower environmental impact as it uses less hazardous chemicals (Ruiz *et al.* 2008).

[30] Most pretreatments are done through physical or chemical means. Physical pretreatment refers to physical size reduction of biomass. Chemical pretreatment refers to the removal of chemical barriers so that enzymes can have access to cellulose for microbial reactions. To achieve higher efficiency both physical and chemical pretreatments are typically required in the production of second-generation bioethanol.

Following pretreatment, the next stage in the bioethanol production process is hydrolysis. There are basically two ways of producing second-generation bioethanol from biomass residues and waste. One production process is acid treatment, which refers to the transformation of biomass material into gaseous carbon monoxide and hydrogen. The output from this process is then neutralised and fermented to produce ethanol. A significant disadvantage of acid treatment is that the hydrolysis stage is harsh and toxic degradation products are produced, which interfere in the fermentation stage. A second production process is enzymatic hydrolysis. This refers to the pretreatment and hydrolysis of biomass material using industrial enzymes to break cellulose into sugar monomers followed by fermentation and distillation (Cortez 2010). Enzymatic hydrolysis can be carried out separately from the fermentation stage, a process known as 'separate hydrolysis and fermentation' (SHF) or both processes can run simultaneously, a process known as 'simultaneous saccharification and fermentation' (SSF) (Soccol *et al.* 2010). Enzymatic hydrolysis can be achieved at relatively mild conditions, in this way enabling effective cellulose breakdown without the formation of degradation products that would otherwise inhibit enzymatic activity (Almeida *et al.* 2007). Enzymatic hydrolysis contributes to the total costs of second-generation bioethanol production; therefore, it is essential to minimise the use of industrial enzymes, while maintaining the efficiency of converting biomass through pretreatment and enzymatic hydrolysis (see for instance Yu 2016).

4.4.2 Bioethanol production in Brazil – a brief overview

The high cost of gasoline in Brazil towards the end of the 20th century stimulated the development of process technologies for the production of economically viable bioethanol from various feedstocks as an alternative to fuel imports. The country has a long tradition of sugarcane breeding and technology development for the production of sugar and bioethanol, and Brazil is today considered a global market leader in bioethanol production (Andersen 2015).[31]

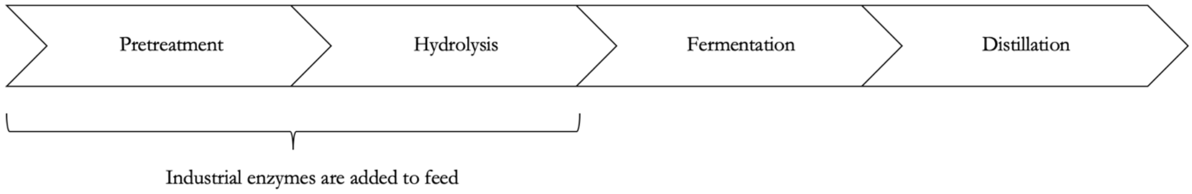

Figure 3 Second-generation bioethanol production process

[31] According to the Brazilian Sugarcane Industry Association, in 2015, approximately 9 million hectares of sugarcane under cultivation produced 665 megatons of harvested sugarcane, resulting in roughly 33 megatons of sugar and 31 billion litres of bioethanol (UNICA 2017). The national production capacity is surpassed only by the United States, which in 2015 produced approximately 57 billion litres of bioethanol. Combined, Brazil and the United States account for 85% of global bioethanol production (Salles-Filho *et al.* 2017).

Bioethanol production from sugarcane took off in the 1920s with the establishment of the Institute of Sugar and Alcohol, set up to help govern the regulation of sugarcane production – see Andersen (2011) for a comprehensive description of the history of the bioethanol industry in Brazil. After the first oil crisis in 1973, the Brazilian government created the ProAlcool programme in 1975 to develop new sources of energy from sugarcane. ProAlcool led to the establishment of a large number of bioethanol plants, based on the sugarcane industry already established and with existing sugarcane processing mills. Consecutive Brazilian governments have since taken steps to increase demand for bioethanol, including the implementation of blending mandates for biofuels and tying gasoline prices to global oil prices rather than subsidising gasoline for consumers. Furthermore, industrial programmes by the National Bank for Economic and Social Development (BNDES) and the Brazilian Innovation Agency (FINEP) have been established to spur innovation (Mazzucato and Penna 2016). A critical impetus for demand was the introduction of flex-fuel engines in the early 2000s, which could use either full bioethanol or gasoline or a mixture of them in any proportion. As indicated in several studies, there is a strong correlation between the increase in consumption of bioethanol and the introduction of flex-fuel light vehicles in Brazil.[32]

The technological advance in Brazil has been to use sugarcane bagasse not only for the production of heat and electricity – the factor that often creates a positive energy balance in bioethanol production – but as a feedstock for the production of second-generation bioethanol (Lopes *et al.* 2016). Several studies highlight and stress the complementarity between first and second-generation bioethanol production processes and the positive synergies with respect to economic exploitation of sugarcane bioethanol production and electricity generation in Brazil (see for instance Dias *et al.* 2012).[33] Moreover, Brazil has a long history of successful genetic breeding programmes (e.g. Brasileiro *et al.* 2014, Landell *et al.* 2014). These have contributed significantly to innovation in the bioethanol industry not least by reducing time to market for new sugarcane varieties developed in the breeding programmes.[34] Other studies stress the status of Brazil as a first mover and highlight its comparative advantages including fertile soils, intense solar radiation, and abundant water supply coupled with the significant technological advances and production increases made over the past decades (see for instance Furtado *et al.* 2011). Combined, this highlights the unique capacity of Brazil to expand bioethanol production without affecting food supply (Trindade 2009, Hall *et al.* 2011, Bordonal *et al.* 2015).

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[32] Bioethanol is competing with conventional fuels such as gasoline. Gasoline and bioethanol are not perfect substitutes because of differences in energy content. As a rule of thumb 0.7 litres of gasoline is equivalent to 1 litre of bioethanol. Thus, the price of bioethanol should be under 70% that of gasoline in order to be competitive in the market. Choosing whether to produce bioethanol or sugar in the sugar mills, therefore, depends on the relative prices differences and is often a rational short-term decision (see for instance Soccol *et al.* 2005).

[33] The bulk of bioethanol in Brazil is made from sugarcanes in refineries, which also produce sugar and generate electricity from bagasse and straw.

[34] The crossing of ancestral sugarcane types with commercial hybrids in the breeding programmes have resulted in robust sugarcane crops, which are more resistant to pests and diseases, have greater longevity, higher fibre content, and greater productivity than conventional sugarcane breeds.

In summary, the Brazilian bioethanol industry has made significant advances in all stages of the innovation cycle and bioethanol should in principle be competitive with gasoline in terms of price (Soccol *et al.* 2010, Goldemberg 2013, Souza *et al.* 2014, Figueiredo 2017). However, although Brazil has developed an important domestic market for bioethanol production, reflecting the positive impact of investments made over the past decades for increasing both technological and productive capacities, the bioethanol industry has come to something of a standstill. The currently low prices of oil and gas have reduced future demand for bioethanol and led to a sharp decrease in investment, both in terms of opening greenfield plants and expanding existing ones. Besides, Brazilian governments have over the years adopted a fiscal policy of controlling inflation based on the regulation of gasoline and other oil derivatives (Araújo 2016). Moreover, Brazil is currently exploring several newly discovered offshore oil and gas fields. These contradictory signals have strongly influenced investment behaviour and, as pointed out by Harvey and Bharucha, 'in Brazil, within the context of low global oil prices, a pro-poverty pro-oil politics of recent years has contributed to the negative environment for further biofuel innovation and development' (2016:87). Nevertheless, the recently launched RenovaBio programme by the Brazilian Ministry of Mines and Energy is designed to expand the production and consumption of bioethanol in Brazil. In effect, a cap and trade system, RenovaBio will assign carbon intensity ratings to bioethanol producers. Fuel distributors will be required to meet specific emission reduction targets based on the fuels sold and are thereby incentivised to improve bioethanol sales at the expense of gasoline.

Although the domestic market for bioethanol still has room for further growth and expansion, it is argued to be insufficient to change the direction of innovation (Salles-Filho *et al.* 2017). There is considerable uncertainty concerning the future development of the bioethanol industry, as the established competitive advantages concerning first-generation bioethanol production currently do not provide a basis for the transition to second-generation bioethanol. As reported by Souza *et al.* (2015) much of the industrially relevant research conducted by public and private knowledge institutes in Brazil fails to be adopted by private sector organisations. Equally important, the Brazilian bioethanol industry is strongly dependent on expanding exports. In 2014, the United States exported 2.9 billion litres of bioethanol compared to 1 billion in Brazil. These figures reflect the present relatively small international market for bioethanol (around 5 billion litres of bioethanol). Any efforts to develop second-generation bioethanol on a commercial scale have to be supported by specific government policies to make bioethanol a global commodity (Araújo 2016). Industrial programmes based on policy support for innovation in the private sector is likely to be ineffective if they stand alone in a scenario in which bioethanol producers have little or no incentives in changing their technological trajectories (Salles-Filho *et al.* 2017).

4.4.3 Novozymes in Brazil

Novozymes is a global biotechnology company headquartered in Copenhagen, Denmark. The company was founded in 2000 following a demerger from Novo Nordisk, a Danish multinational pharmaceutical company specialising in diabetes care. Novozymes develops and produces industrial enzymes and microorganisms, which are used to replace chemicals and reduce energy, water, and raw material use in a variety of industrial processes. In 2016, the company helped its customers and suppliers to mitigate an estimated 69 million tons of carbon dioxide emissions through the application of industrial enzymes. Novozymes holds an estimated 48% of the global enzyme market, which makes it the largest producer of industrial enzymes worldwide. Its products and solutions are sold to more than 40 different industries worldwide. This requires not only strong upstream coordination of innovation and technological development in the value chain, but also an effective downstream network for integrating solutions in the industrial processes of its customers and suppliers. In 2016, Novozymes reported earnings of approximately USD 2.1 billion. Novozymes invests, on average, 14% of annual sales in R&D and has an extensive patent portfolio with more than 6,500 granted patents. It employs around 6,400 people, of whom approximately 1,400 work in R&D. The company has production facilities in Argentina, Brazil, Canada, China, Denmark, India, the United Kingdom, and the United States. Furthermore, it maintains a global innovation network with R&D sites located in Brazil, China, Denmark, India, Japan, the United Kingdom, and the United States (Novozymes 2017).

The history of Novozymes in Brazil began in 1975 with the establishment of a Novo Nordisk subsidiary in the municipality of São Paulo in the state of São Paulo. A local sales office with 5 - 10 staff was set up for the purpose of marketing and sale of Novo Nordisk products in Brazil. In 1989, to keep up with the growing demand for its industrial enzyme products in Latin America, Novo Nordisk decided to increase its production capacity in the region and relocated to Curitiba, Paraná, where it established production and supply chain facilities. The primary purpose of building the manufacturing site was to deliver enzyme products for the growing detergent and starch industry. Over the next decade, the subsidiary developed strong production capabilities, which improved its operational efficiency and the cost and performance of its enzyme products and services. During this period, Novo Nordisk started to diversify its portfolio of industrial enzymes in related markets, including the food and beverages and household care. The continuous technical support from the parent company in Denmark combined with the in-house interaction between different engineering teams allowed for learning and knowledge sharing beyond the existing product categories, thereby diversifying and strengthening the subsidiary's knowledge base in enzyme production.

In 2007, following the demerger from Novo Nordisk, Novozymes Latin America Ltda. (hereafter Novozymes) started experimental development of its Cellic CTec technology to explore the potential of higher bioethanol yield from sugarcane for the purpose of expanding into the Brazilian bioethanol industry.[35] Aided by R&D sites in Denmark and the United States, a research collaboration started with Centro de Tecnologia Canavieira (CTC) through which Novozymes tested Cellic CTec in a pilot plant with a small production capacity of about a 1000 litres of cellulosic ethanol per day.[36] At the time of announcing the partnership with the CTC, CEO of Novozymes, Steen Risgaard explained that the objective of the research collaboration was part of an ongoing effort, 'to identify economically profitable processes within the development of biofuels from plant waste and other biomass' (Novozymes 2007).[37] In 2008, CTC filed a patent for the enzymatic hydrolysis process, which had been developed as part of the partnership with Novozymes. As an innovation, enzymatic hydrolysis was new to the market in Brazil and represented a competitive advantage compared to conventional processes used to obtain bioethanol. Part of the novelty was that enzymatic hydrolysis allowed for full integration in the existing infrastructure of first-generation bioethanol plants. In addition to the potential of reducing the overall operating costs, the integration of enzymatic hydrolysis provided an alternative solution to the problem of excess fermentation and distillation capacity, which were two steps in the production process, where conventional ethanol plants typically experienced significant downtime.

In 2009, Novozymes announced a technology partnership with Cetrel, an environmental protection company, offering treatment and final disposal of effluents and industrial residues, to explore ways to turn bagasse into biogas to produce electricity for Brazilian bioethanol plants. In 2010, Novozymes signed a similar technology cooperation agreement with Dedini, a major Brazilian supplier of ethanol plant technology. A memorandum of understanding was signed between the two companies to cooperate on the further development of second-generation bioethanol process technologies. One of the objectives was to construct a demonstration plant, using Cellic CTec2 to generate proof of concept and validate the integration of enzymatic hydrolysis into the existing first-generation bioethanol plants. Commenting on the partnership, the Dedini Vice President of Technology and Development considered the technology cooperation

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[35] Cellic CTec is a cellulase and hemicellulase complex that ensures cost-efficient conversion of pretreated biomass materials. Cellic CTec has proven effective for a wide variety of feedstock types. Three generations of Cellic CTec were launched in 2009, 2010, and 2012, respectively. Cellic CTec3 is claimed to be 1.5 times more effective than its predecessor Cellic CTec2. The continuous improvement in biomass conversion efficiency provided by Cellic CTec unlocks a new set of technological opportunities to optimise second-generation bioethanol production (Novozymes 2012).

[36] CTC is located in Piracicaba in the state of São Paulo and is the leading sugarcane technology centre in the world. It was founded in 1969 with a mandate to support the technological needs of sugarcane producers in Copersucar, the largest sugar and alcohol cooperative in Brazil. CTC has contributed significantly to innovation in the bioethanol industry, not least by reducing time to market for new sugarcane varieties.

[37] The research agreement between CTC and Novozymes was signed on 13 September 2007 in Copenhagen, Denmark in the presence of Brazilian president Luiz Inácio Lula da Silva and Danish prime minister Anders Fogh Rasmussen. The research agreement was supported with USD 2.4 million from the EU Seventh Framework Programme for Research with the objective to deliver cost-competitive enzyme blends to produce second-generation bioethanol on a commercial scale.

with Novozymes a significant step in making second-generation bioethanol production in Brazil a reality: 'for two years Dedini has searched for partners to enable a solution on an industrial scale based on the combination of experiences and technologies, which would result in the sustainable production of cellulosic ethanol in Brazil. The partnership with Novozymes will contribute significantly to reaching this objective.' Later that year, Novozymes announced a research partnership with the Brazilian energy company Petrobras to develop new methods to improve cost and performance of second-generation bioethanol production from sugarcane bagasse. This partnership provided Novozymes with the opportunity to test Cellic CTec2 further.

The following year, in 2011, Novozymes completed the construction of its modern large-scale R&D laboratories in an adjacent building to the production facilities in Curitiba. In 2012, the Brazilian biotechnology company GranBio announced plans to construct the first commercial-scale second-generation bioethanol plant in Brazil. Novozymes was contracted to supply Cellic CTec3, while Beta Renewables licensed its process technology, PROESA.[38] The process technology enabled and simplified the pretreatment stage of biomass conversion, which allowed for more effective enzymatic hydrolysis, fermentation, and distillation. Located in São Miguel dos Campos in the state of Alagoas, the bioethanol plant 'Bioflex 1' became operational in 2014 with a nominal production capacity of 82 million litres of bioethanol per year. GranBio created a partnership with Caeté from the group Carlos Lyra for the integration of an adjacent steam and electricity co-generation system fed by bagasse. Beyond meeting the energy needs of the two plants, the boiler generated excess electricity in the order of 135.000 MWh per year, which was sold as an additional source of revenue. This installation was unprecedented and represented the first-time bagasse were used for energy-generating purposes in the Brazilian bioethanol industry.

In 2013, Novozymes established a similar partnership with Raízen to supply Cellic CTec3 to its first commercial second-generation bioethanol plant in Brazil.[39] The previous year Raízen had completed a review of different bioethanol process technologies and concluded that the Canadian company Iogen Energy had the most advanced technology ready for commercialisation. Raízen announced plans to invest nearly USD 1 billion between 2014 and 2024 to install and integrate bioethanol process technology into 8 of its 24 plants across Brazil. The investment would amount

[38] Beta Renewables was established at the end of 2011 as a joint venture between Biochemtex, a company of the Mossi Ghisolfi Group, and the U.S. fund TPG (Texas Pacific Group) with a total investment of EUR 250 million. Beta Renewables operated the first second-generation bioethanol plant in the world. The plant, which is in Crescentino in Italy came into operation in the second half of 2012 and had an annual production capacity of 70 million litres of bioethanol. Beta Renewables owns PROESA, which is a unique lignin-cellulosic conversion technology used in the pretreatment of biomass. PROESA uses steam explosion to break down plant structures, which allows industrial enzymes to act with cellulose fibres more effectively. In October 2012, Novozymes became a shareholder of Beta Renewables through the acquisition of a 10 per cent stake amounting to EUR 90 million. Through this partnership, the two companies agreed to market bioethanol jointly using Novozymes' Cellic CTec3 and Beta Renewables' PROESA technology.

[39] Raízen Energia Participacoes is a $12 billion joint venture between Royal Dutch Shell and Brazilian ethanol company Cosan. In 2017, it was the largest sugarcane producer in Brazil and a market leader in the production of bioethanol.

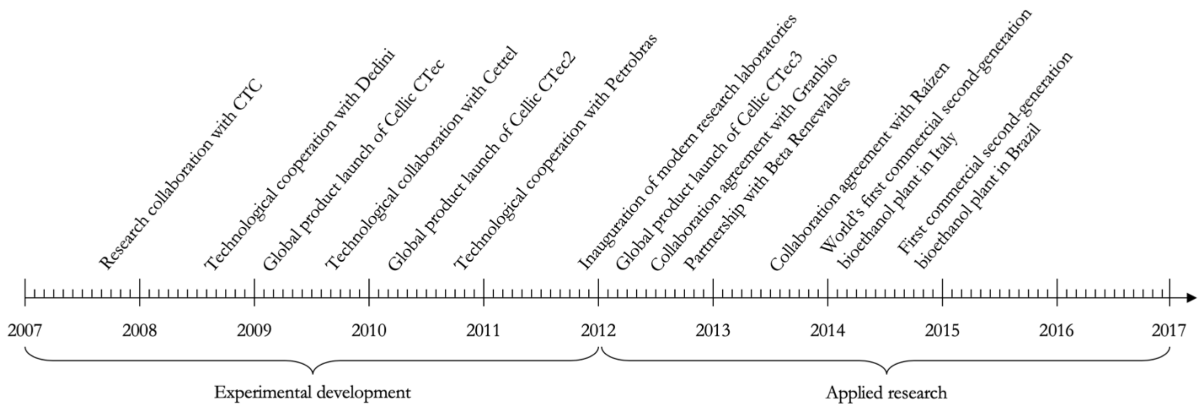

Figure 4 Timeline of Novozymes in Brazil and its bioenergy related activities

to an expected total production capacity of around 1 billion litres of bioethanol in 2024. The bioethanol plant, which became operational in late 2014, was a bolt-on facility to Raízen's sugarcane mill in Costa Pinto, São Paulo. The plant had the capacity to produce 40 million litres of bioethanol a year. Similar to the bioethanol plant constructed by Granbio, Raizen used an onsite electricity generation boiler fed by sugarcane bagasse. During the same period, Novozymes confirmed its intention to expand its enzyme production facilities in Brazil. The investment plan for the factory was, at that time, not completed and ultimately depended on the future demand for bioethanol in Latin America. A timeline of Novozymes and its bioenergy-related activities in Brazil from 2007–2016 is presented in Figure 4.

4.5 Methodology and research design

4.5.1 Case selection

A qualitative single-case design was selected as the appropriate method for research due to the explorative nature of this study. The process of innovation capability building in Novozymes is explored in this study as the internal organisation of capabilities to manage the relationship between the STI and DUI modes of learning in the progression to qualitatively different categories of R&D activity. Specifically, this study aims to identify how changes to the relative importance of science-based and experience-based learning modes influenced capability building from intermediate to advanced innovative capabilities in Novozymes over a 10-year period. Empirical evidence gathered from fieldwork in Brazil established a deeper insight into the observed reality and allowed conceptual constructs to emerge from the analysis process itself. This allowed the close observation of a contemporary phenomenon in a way that goes beyond a static picture, thus examining not only the relationship between the conceptual constructs described in the previous sections but also how the content of these relationships evolves over time. The detailed empirical findings provide new insights with a high level of validity owing to the possibility of including changing dynamics and contextual conditions in the analysis. However, the aim of the study is not to generate findings that are generalisable in a statistical sense, but rather to contribute to theory development through analytical generalisation. Although this case focusses on a Brazilian subsidiary of a global biotechnology company, the creation and accumulation of innovation capabilities, here understood as an interactive learning process conditioned by national innovation systems, is suggested to be of relevance to a broader range of actors in developing countries.

4.5.2 Data collection

The case study draws on the following three sources of data: (1) interviews, (2) participant observations, (3) documentary evidence. Following a meeting with the Vice-President for R&D at Novozymes in Denmark in November 2015, the data for the study were collected during fieldwork in Brazil in 2016 and 2017. To obtain a full description of innovation capability building in Novozymes, 25 in-depth semi-structured interviews were conducted at its premises in Curitiba in the state of Paraná. The interviews were conducted with employees from the R&D department across different hierarchical levels, ranging from trainees, engineers, and scientists to the R&D manager. Moreover, to gain insights into the strategic mandate of the subsidiary, interviews were conducted with the Vice-President and President of Novozymes. This allowed to contrast views from the interviewed group, which is argued to enhance the construct validity of the findings (Adcock and Collier 2001). An interview guide with open-ended questions and covering relevant themes was prepared and followed during the interviews. First, interviewees were asked to provide a description of the overall history of Novozymes in Brazil. A set of more general questions was directed at identifying the number and qualifications of the scientists and engineers, while specific questions aimed at obtaining a detailed understanding of the technical milestones and achievements of the R&D department. Second, the interviewees were asked to identify the main learning mechanisms used in industrial enzyme technology development and to reflect upon if and how changes to the nature of these had influenced the underlying learning processes of appropriation and application. The interviews tended to begin with broad generalisations, but with encouragement, the interviewees gave explanations and concrete examples of specific learning mechanisms. Third, the interviewees were asked probing questions about specific changes to the research and experimental development activities conducted in Novozymes with the objective of generating a detailed account of the novelty and significance of its innovative activities over time. A change in technological activities could, for instance, involve a shift from routine-based and labour-intensive engineering tasks, such as detailed technical drawings and calculations, to more complex knowledge-intensive tasks, such as basic and conceptual engineering.

Such change could also be discerned in the ability of Novozymes to execute specific and well-defined problem-solving tasks to actively engage in the framing of complex problems to be solved using scientific methods of extrapolation of a known concept to an unknown end.

Participant observations in the R&D department and its research laboratories allowed an immersion in the innovation climate of Novozymes and an insider view of its daily activities. This provided a unique opportunity to witness the organisational context in which innovation happens and allowed for an in-depth understanding of Novozymes' approach to innovation, which would have been unobtainable from passive observation. To obtain a practical understanding of the different stages in the bioethanol production, field visits were made to the sugarcane and bioethanol producer Ipiranga Agroindustrial S.A in Mococa in the state of São Paulo. Documentary evidence included (1) strategic and organisational documents, such as annual reports and organisation charts, (2) industry and competitive reports, (3) presentations and newsletters.

To make sense of the vast amount of collected data, an attempt was made to write a narrative of innovation capability building in Novozymes. To recover empirical evidence from the earlier period of innovation capability building, different sources had to be combined, such as annual reports, newsletters, and interviews with former employees, including the previous R&D manager. This offered not only a basis for the analysis but also highlighted relevant links between key events in the history of Novozymes. The data collected from interviewees together with field notes from participant observations were organised into thematic categories using a sequential timeline matrix, as described in Miles and Huberman (1994). These categories comprised separate tables in which direct interview quotes could be inserted within two overarching themes related to (1) STI and DUI modes of learning, (2) innovation capability levels. Correspondingly, the learning mechanisms identified from the data collection were grouped as processes of appropriation or application and qualitatively assessed based on the features in the framework for interactive learning. The criteria used to assess the learning mechanisms are described in Table 8.

Table 8 Criteria to assess the key features of individual learning mechanisms in Novozymes

	Classification:	Qualitative criteria and ratings:
Variety	Absent	Learning mechanism was not implemented during the period examined.
	Emergent	Learning mechanism was being implemented during the period examined.
	Present	Learning mechanism was implemented and used during the period examined.
Intensity	Intermittent	Learning mechanism was used intermittently during the period examined.
	Continuous	Learning mechanism was used continuously during the period examined.
Functioning	Poor Moderate Good	This feature was classified and rated by combining (1) comments and opinions of the interviewees, (2) field notes from participant observations in the R&D department and research laboratories, (3) systematic search into the archival records of Novozymes.

4.6 Innovation capability building in Novozymes

The process of innovation capability building in Novozymes is roughly divided into two phases and corresponding levels of innovative capability based on the empirical data collected and analysed: 'intermediate' between 2007–2011 and 'advanced' between 2012–2016 (see Table 6). This first part of the analysis explores the effort of Novozymes to create and accumulate innovative capabilities in enzyme technology development for second-generation bioethanol production in Brazil. Against this background, the second part of the analysis pertains to the individual learning mechanisms used by Novozymes in the gradual progression from the intermediate to advanced level of innovative capability and the relative importance of the science-based and experience-based learning modes. Before turning to the two main phases of analysis, (2007–2011 and 2012–2016, respectively) the period leading up to 2007 is briefly described.

The empirical evidence suggests that in the period from the early 1990s to 2006 Novozymes accumulated advanced production capabilities, adopting not only enzyme technologies developed in Denmark but also integrating these with local components, process technologies, and manufacturing infrastructure, such as laboratory control and logistics systems. The parent company initially assigned managers and skilled personnel from Denmark with prior industrial experience, who began to organise and supervise engineering teams that worked closely together to run the green field manufacturing site in Brazil. Reflecting on these early years, the former Vice-President of Novozymes recalls, 'in the 90s, we used to have Danes down here, in production, in finance. … it was a learning process because these were talented guys, very high experience. We learned a lot with them. …This was decisive to keep this plant running at that point.' In addition, engineers were regularly sent to manufacturing sites in Denmark and trained in standard operating procedures and processes, ensuring that the enzyme products and solutions met company quality and efficiency standards. To summarise, during this early period, Novozymes developed increasingly complex operational activities from initially performing standardised procedures and routine-based engineering tasks aimed at sustaining production output at pre-set levels of efficiency towards the accumulation of basic innovative capabilities and a more dynamic and creative engagement with existing technologies and production systems.

Between 2007 and 2016 the continuous optimisation of successive generations of Cellic CTec to local market conditions and raw material characteristics allowed Novozymes to develop increasingly complex customer-specific solutions in Brazil. In the early phase between 2007 and 2011, the R&D department started to recognise similarities within the assembly of components of the technological system. The complexity of configurations at different hierarchical levels was gradually reduced to more manageable forms Novozymes started to develop a tacit understanding of working with Cellic CTec. In the later phase between 2012 and 2016, Novozymes improved the engineering design and technological parameters of the bioethanol production process through feedback gained from user-producer interaction. The diversification of the knowledge base, in turn, led to improved experimentation and testing in the research laboratories. Combined, the deliberate and continuous effort to improve the appropriation and application of knowledge in enzyme technology development resulted in an accumulation of innovative capabilities. Although the balance between the STI and DUI modes of learning during the innovation capability building process in Novozymes is difficult to discern, changes to this relationship can be appreciated by considering the changes from experimental development to applied research activities in detail.

4.6.1 Experimental development based on the DUI relative to the STI mode of learning (2007–2011)

In the early phase between 2007 and 2011, Novozymes was mainly involved in experimental development. An integrated approach ensuring process compatibility with existing bioethanol plants was needed to establish a platform to produce second-generation bioethanol in Brazil. Accordingly, experimental development of Cellic CTec was undertaken to develop cost-effective and industrially viable process options for converting sugarcane bagasse into fermentable sugars. Practical technical problem-solving through iterative processes of trial and error at the customer sites played a significant role during this period, in which the generic properties of Cellic CTec were applied to sugarcane substrates under different process conditions. Through incremental improvement of engineering practices and experimental designs, the scientists and engineers gradually started to develop a tacit understanding of the relationship between structure and function of the technological system and how the modification of Cellic CTec in concrete situations affected functionality and performance. The learning and experience gained from solving practical technical problems in concrete situation allowed Novozymes to acquire and build up a minimum base of knowledge in second-generation bioethanol production. This experience-based mode of learning based on doing, using and interacting relationships encountered in the interaction with customers and suppliers in the Brazilian innovation system in the early period between 2007 and 2011 provided Novozymes with a sense of opportunity and potential of Cellic CTec, and allowed the scientists and engineers to create and accumulate advanced innovative capabilities needed to progress to applied research in industrial enzyme technology development.

4.6.2 Applied research based on the STI and DUI modes of learning (2012–2016)

In the later phase between 2012 and 2016, next to the experimental development of Cellic CTec, Novozymes gradually became more involved in applied research. Following the inauguration of its modern large-scale research laboratories in 2011, a deliberate effort was made to better understand the relationship between the structure and function of Cellic CTec. The objective of the search was to gain a holistic understanding of second-generation bioethanol production and how the different stages change with respect to enzymatic hydrolysis This effort was deliberately undertaken to determine new methods of developing customer-specific solutions based on local market conditions and raw material characteristics in Brazil. As explained by the R&D manager, 'Novozymes changed its strategy from developing global products to deliver customised solutions to our strategic customers. It was a customer-oriented approach. We realised there are specific requirements according to the nature of the feedstock and the pretreatment conditions applied in the customer process that play an important role in the performance of the enzymatic solutions. So that was the reason we started optimising and become more customer oriented.'

Hence, in the later phase, the science-based mode of learning based on science, technology and innovation relationships started to gain importance relative to experience-based learning, as Novozymes needed to appropriate the knowledge necessary to understand the relevant technological parameters influencing the different stages of second-generation bioethanol production. One of the most significant characteristics in the progression from experimental development to applied research activities in Novozymes was the gradual maturation of the underlying sciences, which contributed to build a scientific understanding of the technological systems and the domain within with the search for technological solutions was undertaken. Based on experimentation and testing of sugarcane substrates and their biochemical characterisation, knowledge was appropriated and organised into frameworks and categories, resulting in a multifaceted knowledge base with various application domains. At the same time, the continuous experimental development at the customer sites allowed Novozymes to gain extensive feedback from user-producer interaction on technological parameters of the bioethanol production process.

The deliberate and combined use of the science and experience-based modes of learning, and naturally a more interactive learning process, in the later period was highly dependent on the prior knowledge base and practical experience. In other words, the build-up of a minimum base of knowledge in bioethanol production, that informed and guided practical technical problem-solving in the interaction between Novozymes and its customers and suppliers in the early phase between 2007 and 2011, allowed the scientists and engineers to develop more accurate simulations in the research laboratories in the later phase between 2012 and 2016 and to gain a better understanding of enzymatic hydrolysis with respect to the different bioethanol production stages. Illustrative examples of the gradual progression in Novozymes from experimental development to applied research activities over the period of analysis are presented in Table 9.

Table 9 Innovation capability building in Novozymes (2007–2016)

	Experimental development (2007–2011)	Applied research (2012–2016)
Search	Systematic search for existing configurations realises the potential for commercially viable process options and a higher bioethanol yield from enzymatic hydrolysis using successive generations of Cellic CTec.	Original investigation deliberately undertaken to search for new configurations in the technological system, providing a more holistic understanding of how the stages of bioethanol production change with respect to enzymatic hydrolysis.
Activity	Problem-solving through iterative processes of trial and error, in which the generic properties of Cellic CTec are applied to sugarcane substrates, leads to a basic understanding of the different stages in bioethanol production.	Problem framing through improved insight in the simulation of different stages of the bioethanol production process leads to the advanced optimisation of Cellic CTec based on local market conditions and raw material characteristics.
Output	The build-up of a minimum knowledge base and incremental development of basic research methods and screening techniques allow for improved understanding and more accurate simulations, leading to incremental increases in the functionality and performance of Cellic CTec.	The diversification of the knowledge base and development of advanced research methods and guided screening techniques allow for the advanced optimisation of Cellic CTec, resulting in increasingly complex customer-specific solutions optimised to local raw material characteristics.

The phases of experimental development (2007–2011) and applied research (2012–2016) are assessed based on the criteria outlined in the taxonomy of R&D activities

4.7 Individual learning mechanisms used in innovation capability building in Novozymes

The second part of the analysis pertains to the relative importance of science and experience-based learning modes in Novozymes in the gradual progression from the intermediate to advanced-level innovative capability. Six learning mechanisms are distilled from the empirical data collection (see Table 4). These are categorised as processes of appropriation or application and qualitatively assessed based on the features in the framework for interactive learning (see Table 5). Although cumulative in nature, an attempt is made to capture changes to the individual learning mechanisms based on their variety, intensity, and functioning (see Table 8). The identified changes to the individual learning mechanisms between 2007 and 2016 are highlighted in italic in Table 10.

4.7.1 Intermediate innovative capability based mainly on experience-based learning mechanisms

Novozymes did not innovate in isolation but in close partnership with its customers and suppliers. It was through continuous user-producer interaction in the Brazilian innovation system that Novozymes gained the feedback and inputs necessary to conduct experimental development and optimise its enzyme technology to better fit local market conditions and raw material characteristics in Brazil. Reflecting on the learning and experience gained from user-producer interaction and practical technical problem-solving in the early phase of experimental development between 2007 and 2011, one of the research associates explains: 'We have the ideas, the solutions that we think might work, but we only know how the enzymes are going to react after we try them in the *usinas* [sugarcane processing mills] and have their inputs and feedback. So this relationship between Novozymes and our partners has to be very strong.'

Through continuous and iterative processes of trial and error, incremental modifications were made to the configuration of Cellic CTec and applied in small-scale experiments to simulate different process conditions. Data and results from simulations and experimental designs were disseminated and interpreted in daily and weekly meetings, seminars, and brainstorming sessions. Moreover, internal training and development functioned as an effective way to apply knowledge in enzyme technology development through close collaboration and direct instruction. Under the supervision of senior scientists, research associates gained practical experience from working with the pretreatment of biomass (e.g. basic experimentation with adjusting pH levels, dosage, and temperature of enzyme blends). Continuous on-the-job training provided learning opportunities, where new employees were coupled with senior scientists, who supervised the skill development and training of the employee in what resembles master-apprentice relationships. The establishment of these formal relationships functioned as an effective way to pass on knowledge through close collaboration and direct instruction. At the same time, the R&D department established a close working relationship with 'Technical Services', an adjacent group which ensured Novozymes customers and suppliers had direct access to a full and experienced engineering team for troubleshooting all parts of the enzymatic hydrolysis stage and its technical and practical operation. Daily collaboration between the two groups was close, and employees deliberately swapped between the two groups to gain both practical engineering and research experience. Through the rotation of employees from various research projects and cross-functional teamwork, the scientists and engineers established a basic level of insight into second-generation bioethanol production. Moreover, Novozymes developed a range of internal web-based training seminars in a wide range of areas such as project management, safety and risk assessments, quality management, lean manufacturing, data protection policy, intellectual property rights, and other related fields.

This combination of practical technical problem-solving, user-producer interaction, and continuous internal training and development of the scientists and engineers in the R&D department of Novozymes was important for building a minimum knowledge based in second-generation bioethanol production in Brazil. As explained by one of the scientists, 'in the beginning, the knowledge we had about the 2G [second-generation bioethanol] was limited. The first step was to start the R&D department. Otherwise, you wouldn't have the room to put this kind of thinking here. We didn't know much about the process, and we didn't have any of the sugarcane mills working. Now we are learning with them because the plants are starting to run, and they are having all kinds of mechanical issues. We are in the very beginning of this industry, so the first problems are in the engineering part. So, there are all these technical problems popping up now, and we are learning with them. What the problems are and what we need to solve. Later, as they solve this problem, the bottleneck will move forward in the pipeline of production and hydrolysis will be a problem. Then we will start to see the real problems with the enzymes. In my opinion, we are still in the process of gathering knowledge and capabilities.'

The R&D department started working informally on developing the research methods and procedures needed to eliminate whole classes of enzymes and to direct the search into an area of the technological system, where the solutions were more likely to be found. Nevertheless, since no formal protocols existed when Novozymes started experimental development in Brazil, the scientists and engineers initially relied on various research methods and procedures.[40] Asked to give an example of how the categorisation of configurations in the technological system was undertaken in the beginning, one of the trainees explains: 'when I started working here, we used an excel sheet to document and categorise the screening of different enzyme strings. … Over time, we have gotten better at using Sequoia [an internal knowledge management tool], but this was through an active effort from my manager. He wanted us to standardise the way we manage knowledge of the enzymes.' Relatedly, the R&D manager actively encouraged the scientists and engineers to subscribe to relevant scientific journals and to take advanced industrial courses in bio-product and process engineering, as well as professional skill development courses in areas such as leadership and management, personal effectiveness, teamwork, and competency development. The continuous training and development of the employees contributed to not only strengthening the knowledge base of Novozymes but also benefited the professional and personal development objectives of the scientists and engineers (Novozymes 2009).

Over time the improvement to established research methods and procedures permitted the scale-up of experiments in the laboratories, which led to new insights on how to improve the different stages in the bioethanol production process. The difficulty with controlling contextual variables in the upscaling required a unique solution to cater for each enzyme. Lead enzymes are expressed in microorganisms such as yeast or fungi. It is therefore important to verify how the microorganism act when grown on different types of biomass and which sequence of catalysts that

[40] Today Novozymes organises and manages industrial enzyme technology development in an innovation funnel consisting of four successive phases. The process typically starts with the formulation of a creative idea or solution to a technical problem, which is extrapolated by the scientists and engineers based on the prior knowledge base and practical experience. The potential of the 'new lead' is considered by the Industrial and Strategy Group, which evaluates the business prospect and fit with the strategy of Novozymes. Next, the Research & Development Management assesses the technological feasibility of the idea. Lastly, the Patent Portfolio Group analyses the 'freedom to operate' and the possibility of patenting the idea. Upon passing the strategic and technical evaluations, the 'new lead' enters the 'discovery' phase, in which thousands of different enzymes are analysed. If single enzymes show potential in terms of reliability and stability, they are cleansed and thoroughly tested to remove any unwanted side effects. The lead enzymes then enter the 'development' phase, which consists of fermentation and upscaling. The search and sift for suitable enzyme candidates involve dynamic feedback and loops between the 'discovery' and 'development' phases to correct any failures and possible disregarded improvements. Hence, the capability of Novozymes to exploit the prior knowledge base to solve any issues arising during the process is imperative for success. If the exhaustive tests of the lead enzymes indicate a successful product, they move into the final 'launch' phase.

are necessary to deconstruct the biomass. For instance, yeast is especially attractive as it is tolerant to high ethanol and inhibitor concentrations and can grow at low pH values which reduce bacterial contamination. The ability of the fermenting microorganisms to use the whole range of sugars available from the hydrolysis is essential to increase the economic competitiveness of second-generation bioethanol production. Importantly, the combined innovation process did not happen in a single R&D site but through a carefully orchestrated research collaboration in the global innovation network.[41] In the case of Cellic CTec, the pilot scale fermentation and production took place at the R&D site in the United States. The enzymes were then imported to Brazil and tested on different substrates. One reason that optimisation studies were performed in Brazil was due to complex Brazilian legislation, which made it difficult to export substrates abroad. More importantly, the optimisation of Cellic CTec to local market conditions and raw material characteristics required constant user-producer interaction in the Brazilian innovation system.

During the early phase of experimental development, the R&D department also started to incorporate quality management into its daily engineering practices and research activities. The quality management system of Novozymes covered a formalised approach that documented the processes, procedures, and responsibilities for achieving quality policies and research objectives. Standardisation ensured that all products, processes, and solutions were developed and documented in compliance with national and international legislation. To establish adequate quality management into its daily routines and activities, the scientists and engineers started to identify and document various functional processes organised in vertically structured departments. The R&D department started to document best practices and procedures into quality systems manuals, which were updated on a continuous basis. Every employee was responsible for evaluating and updating the standard operating procedures associated with working at Novozymes. This deliberate and continuous effort, among other things, led to Novozymes being awarded certifications ISO 14001 and 9001 in 2004 and 2008, respectively. The learning and experience gained from this more formalised approach to industrial enzyme technology development are important to understand how Novozymes started to appropriate the knowledge necessary to optimise Cellic CTec to local market conditions and raw material characteristics in Brazil.

Moreover, during the early phase of experimental development, Novozymes started to develop knowledge linkages with some of the leading universities and research institutes in Brazil, not least the research collaboration started with the CTC in 2007. External research collaborations served as a way not only to appropriate knowledge from knowledge institutes in the Brazilian

[41] Each R&D site of Novozymes represents a specific set of skills and competencies, which are tied together by the knowledge management system. See Haakonsson and Ujjual (2015) for a detailed analysis of the internationalisation of R&D in Novozymes.

innovation systems but also facilitated access to specialised analytical instruments and equipment. The latter proved particularly pertinent as the research activities in the R&D department grew more complex As one of the research associates explains it, 'in the beginning, what we did here was mainly trial and error ... but this had the disadvantage that we never knew what was going on. To develop a better enzyme product, we needed to learn what was going on. So, we tried to get more basic research into our site and the easiest way to do this was to get in contact with universities because they had the brains and the equipment.' External research collaborations were formed mainly because many of the trainees and scientists who started working in the R&D department had formed extensive networks as part of their academic studies with the very same university departments and research institutes with whom Novozymes sought to collaborate. Nevertheless, many of the scientists and engineers observe that from the beginning, Novozymes was faced with the difficulty of sharing on an equitable basis the costs and benefits of research. This pertained particularly to the intellectual property rights arising from external research collaborations. For that reason, the learning and experience gained from collaborating with Brazilian knowledge institutes were fairly modest and mainly involved outsourcing analytical tasks on a contractual basis, whereby Novozymes leased specialised equipment that was not readily available in the R&D department. Asked to give a specific example of how external research collaborations complemented industrial enzyme technology development in Novozymes, one of the scientists explains, 'we are planning to do a contract and they (the Federal University of Paraná) provide us with a service. We want to do a characterisation of the molasses to learn exactly what we see in the fermentation. This will improve the way we do the experiments here ... we know that the enzymes work, but we do not know why. We need to have this kind of basic research to know exactly how we are going to optimise the enzymes.' As a way to further strengthen external research collaborations in the Brazilian innovation system, Novozymes also recently started to host PhD student and postdoctoral researchers in the R&D department as part of joint research projects with universities and research institutes in Brazil.

Between 2007 and 2011, as the experimental development activities grew more complex, Novozymes devoted considerable time and effort to find people with the right technical skill set and research experience. The learning and experience gained from hiring experienced R&D managers and scientists were important to appropriate the knowledge needed to improve industrial enzyme technology development in Brazil. Most of the engineers employed at Novozymes had graduate degrees in bioprocess engineering or related technical fields (e.g. organic chemistry or microbiology). The Federal University of Paraná offered a degree in biotechnology and bioprocess engineering, and the candidates offered traineeships at Novozymes were typically selected from this programme. Upon completion of their academic studies, successful trainees were offered positions as research associates. As pointed out by one of the senior scientists, the value of having engineering candidates gather practical experience in enzyme technology development early on in their career was of great value to Novozymes, 'in Brazil, you usually do not have industry-relevant work in the universities, so this bridge to the industry is pretty hard to find.'

In summary, in the early period of experimental development in Novozymes, learning and experience were mainly based on practical technical problem-solving encountered in interaction with customer and suppliers in the Brazilian innovation system. This experience-based learning combined with the continuous training and development of the scientists and engineers in the R&D department were critical for building a minimum base of knowledge in second-generation bioethanol production. It allowed Novozymes to develop a more formalised approach to industrial enzyme technology development needed to improve the research methods and procedures for optimising biomass conversion to local market conditions and raw material characteristics in Brazil. Reflecting on how changes to the relationship between the science-based and experience-based learning modes influenced the gradual progression intermediate to advanced capabilities, one scientist reasons, 'this also comes with scientific background and experience, and most people here, they are not senior scientists. But then you start to learn how to make things simpler and faster. We are starting to learn and align with the other R&D sites … what you need is someone who understands the industry and who knows how to simulate, at lab scale, the problem that you want to tackle and understands the influence of enzymes in this setup. After that it is a learning process, an accumulation of knowledge you get from these simulations.'

4.7.2 Advanced innovation capability based on the science- and experience-based learning mechanisms

In the later phase of applied research, following the completion of the modern large-scale research laboratories in 2011, Novozymes started to take advantage of a variety of graphical equipment and data-driven approaches to search and sieve entire classes of enzymes and narrow down the number of enzyme strings to a level at which the scientists could manually evaluate the properties of individual candidates. A general problem encountered in biotechnology development relates to controlling upscaling from laboratory to commercial scale.[42] Since 'new leads' were cultured only in small quantities under controlled laboratory environments in Novozymes, the objective during the development phase was to learn whether upscaling at the customer sites was possible.

[42] As argued in the sociology of knowledge, 'universality and context independence are not to be taken as given but must be analysed as precarious achievements' (Mackenzie and Spinardi 1995:44). An important endeavour is how to succeed in obtaining knowledge developed in one context to work in another. In controlled laboratory environments, variables can be changed in a controlled way, permitting a systematic accumulation of deliberately created findings, which add up to robust knowledge. 'The idea is that the phenomena created under such restricted circumstances allow access to background regularities which are valid more generally, at the very least as long as one can recreate the circumstances' (Rip 1997: 11).

Novozymes often had to abandon promising lead enzymes because of insurmountable problems in controlling the production process in the upscaling from lab to commercial scale.[43] For in-depth discussions of the various local specificities and knowledge idiosyncrasies, inherent to natural resources-intensive industries, which may cause unexpected difficulties in the innovation process see Torres-Fuchslocher (2010), Andersen *et al.* (2015), Katz and Pietrobelli (2018). Hence, the ability of Novozymes to exploit the prior knowledge base to solve any issues arising during the innovation process was imperative. Reflecting on how the appropriation of knowledge improved during the later phase, the previous R&D manager explains, 'In the beginning, we started with small incubators … but nowadays we have much more equipment, different kinds of incubators, different setups to run experiments, different methodologies of analysis. Even in terms of analysing the proteins and enzymes, we have some methodologies in place to measure what happens. We also have some analytical capabilities to evaluate the reaction. … there was a very interesting development. The continuous testing and experimentation with configurations in the technological system contributed significantly to the maturing the underlying sciences and to the diversifying the knowledge base of Novozymes. This, in turn, led to the improved research methods and guided screening techniques needed to conduct applied research (e.g. biomass fractionation, determination of kinetic constants, mass spectrometry analysis, molecular modelling, characterisation of inhibitors and catalysts formed during the pretreatment and hydrolysis stages).

Quality management also improved significantly throughout the period of applied research, as the R&D department started documenting best practices and procedures in the form of quality systems manuals, which were updated on a continuous basis, helping Novozymes to coordinate activities to meet global efficiency and quality standards. Besides, the scientists and engineers were intensively trained in the use of a series of internal knowledge management tools specifically designed to categorise and structure the technological system and to equip the R&D department with the skills and methods necessary to search and sieve through the vast amount of information available within the prior knowledge base of the company.[44] As one of the scientists explains: 'This is how we organise things …. we have a timeline registration of all the information, which is really useful. For instance, now I'm developing the new cocktail for Raízen, so it is important to check

[43] The first generation of the product typically consists of several hundred enzyme variants with similar characteristics but with small differences in performance. Through an exhaustive analysis of all the variants, those enzymes which match certain common properties are selected for further analysis. In the second generation of the product, the selected batch of enzymes is cultured with the purpose to test their efficiency.

[44] The knowledge management system in Novozymes, among other things, comprises three integrated tools: (1) LUNA, (2) ELN, (3) Sequoia. LUNA is an electronic document management system used to share knowledge in the form of reports. LUNA reports constitute an important part of the continuous codification of knowledge in the company. These are archived and can be accessed by the relevant peers in company. ELN is a unique electronic notebook solution, which facilitates direct access to more than 250 projects in one language across different sites and time zones. ELN and works as a journal of day-to-day activities to describe and document experiments and results. Prior to ELN the traditional notebooks had been physically tied to the individual lab making it difficult to share knowledge across the R&D sites. ELN also has a unique signing option, which helps Novozymes to secure the earliest possible date of invention as part of the patenting process. Sequoia is a global database in which Novozymes documents all the enzyme strings used in experiments with a unique registration number (Novozymes 2010).

what was done in the past. By using LUNA and ELN, I have an idea of what plans I can go for and which of them do not work.' Reflecting on how the knowledge management contributed enzyme technological development in Novozymes, another scientist explains: 'we have been getting better at this and the best part is the collaboration between the R&D sites. We are seeing how their molecules perform here under our conditions, and we have a good way of storing this data and use it for further improvement.' But learning how to make the most of the knowledge management system took a dedicated management effort. As pointed out by one of the scientists: 'Novozymes has systemically repeated mistakes in the past due to lack of communication with relevant peers. So, we're trying to close this gap and make people more connected.'

The science-based mode of learning combined with the feedback and inputs gained from partnering with its strategic customers and suppliers are central to understand how Novozymes accumulated and diversified the knowledge base and improved its research methods and screening techniques necessary to optimise Cellic CTec to local market condition and raw material characteristics in Brazil. The continuous learning and experience gained from the user-producer interaction in the Brazilian innovation system in the later period of applied research allowed the scientists and engineers to learn how the application of Cellic CTec performed under local conditions. Accordingly, practical technical problem-solving changed from solving specific and well-defined problems to increasingly engaging in problem framing in close collaboration with GranBio and Raízen. As explained by the previous R&D manager, 'we started with a very basic approach, trying to apply existing enzymes to the processes here and trying to adapt the conditions of application. Today, we are actually developing an enzyme, which is customised to these specific conditions. So yes, it has definitely gotten more complex.' The current R&D manager further elaborates this: 'Once we established the partnerships with GranBio and Raízen, we needed to develop the enzymes in collaboration with the partner in a synergy mode. So definitely, yes; when we established the partnerships and the teams got together and talked about the technical details of the production process at the customer site … then we started to improve the different steps of the process and, in that way, optimise not only the overall costs but also the enzyme technology.'

Following the completion of its modern large-scale research laboratories in 2011, Novozymes recruited several highly skilled specialists with a rich contextual understanding of biotechnology applications. The R&D department experienced significant growth, from around 12 scientists, research associates, and a few trainees in 2011 to more than double that by 2016. The basis for this expansion was, among other things, due to Novozymes having successfully established a trainee programme. Nevertheless, an increasingly larger share of the personnel required was engineers with PhD qualifications and specialised knowledge in bioprocess engineering.

Reflecting on the difficulties of finding scientists and engineers with the right competencies, technical skill set, and research experience in bioethanol production, one of the scientists notes: 'Novozymes did not have a lot of industry experience in the beginning, so we had to gather expertise from the market by hiring experienced scientists … we are still struggling with having a closer relationship with PhDs to have projects more related to our area.' For that reason, Novozymes started to explore the possibility of developing an industrial PhD programme in Brazil. The deliberate aim of this initiative was not only to appropriate knowledge through mutually beneficial partnerships with leading universities and research institutes in Brazil but also to be able to apply the results directly in the further development of industrial enzyme technology.

During the later phase of applied research, Novozymes strengthened its research collaboration with several universities and research institutes in Brazil, including the Federal University of Paraná, and the University of São Paulo. For instance, Novozymes frequently invited engineering candidates from the Federal University of Paraná on site visits to learn about the bioethanol production process. Relatedly Novozymes established various formal and informal relationships with several professional associations and business organisations related to biotechnology and bioenergy in the Brazilian innovation system to engage in public policy debates on bioenergy, biodiversity access, and intellectual property rights, and to exchange ideas, share experiences, and learn about different approaches to bioethanol production in Brazil. One example of such engagement was the Associação Brasileira de Biotecnologia Industrial (ABBI), a professional association comprised of leading biotechnology companies with bioenergy activities in Brazil. The formal objective of ABBI was to foster dialogue within Brazilian society about the advancements of industrial biotechnology and to influence relevant stakeholders and policymakers to improve national legislation and patent laws.[45] Brazil has an immense biodiversity, which is believed to comprise 10 - 20% of the total species known. Novozymes was carrying out screening programmes in order to isolate and identify microorganisms capable of producing industrial enzymes. Commenting on the complex and bureaucratic Brazilian Biodiversity Law and Decree, the former regional president of Novozymes explains the value and purpose of participating in professional associations such as ABBI when engaging with policymakers in Brazil, 'this is about biodiversity and access to the genetic patrimony in Brazil. We want to make research and Brazil has five different biomes. Essentially this is about how to take soil samples. The official procedures say okay you can take a sample, and yes, you can send it to Denmark. But there are many rules to be followed. In the past, this used to be a very difficult thing to do.'

[45] Launched in May 2014, the founding members of ABBI were Amyris, BASF, BioChemtex, BP, CTC, Dow, DSM, DuPont, GranBio, Novozymes, Raízen, and Rhodia.

During the later phase of applied research, the continued integration in the global innovation network of Novozymes was essential for the scientists and engineers to appropriate the vast prior knowledge base of the company.[46] Appropriation of knowledge was realised through job rotation (secondments) whereby the scientists and engineers spent periods of time abroad at other R&D sites of the company. Similarly, after the construction of the research laboratories was completed in 2011, senior scientists from the other R&D sites spent periods in Novozymes and supported the R&D department in establishing the adequate research methods, procedures, and protocols necessary to conduct applied research of Cellic CTec in Brazil. As explained by one of the senior scientists, secondments not only created access to knowledge but also facilitated the integration of the R&D department into the global innovation network of Novozymes: 'The R&D manager initially started to send us to visit the other R&D sites and interact with people. That helped a lot when you met people face to face. But then he started demanding answers from us in terms of validating our results with the other R&D sites, the conclusions we were getting from our experiments here in Brazil. Consulting other experienced scientist around the world on the design of the experiments, we were planning.' Highlighting the value of job rotation in Novozymes, the current, as well as the three previous R&D managers all, gained extensive training and experience working in the other R&D sites before taking up positions in the R&D department in Brazil.

In summary, in the later phase of applied research in Novozymes, the STI mode of learning started to gain importance relative to the DUI. Knowledge and experience were appropriated from a combination of science-based learning through improved testing and experimentation in the research laboratories and user-producer interaction through the establishment of several beneficial partnerships with forward-looking bioethanol producers in the Brazilian innovation system. The combination of STI and DUI modes of learning, and naturally a more interactive learning process, allowed Novozymes to appropriate the knowledge necessary to learn how the application of Cellic CTec performed under local conditions and to identify cost-effective enzyme variants and determine the optimal dosing range for maximum yield. As emphasised by the R&D manager, 'we are starting to learn with them, now when we have the full-scale plants up and running. We have already received some good feedback from them in terms of how our enzymes perform in their plants. We foresee a much closer collaboration with both GranBio and Raízen in the future, which will bring more benefits to both sides.'

[46] Studying the extent to which this form of dual embeddedness contributes to innovative performance of latecomer firms in developing countries, several studies find that certain types of highly innovative subsidiaries have successfully developed knowledge linkages between global innovation networks and national innovation systems (e.g. Marin and Bell 2010, Figueiredo 2011, Marin and Giuliani 2011, Meyer *et al.* 2011;,Giuliani *et al.* 2014). These results are complemented by a large body of research in international business studies, which finds that subsidiaries of multinational corporations often are situated to connect local and global knowledge bases in the process of creating and exploiting competitive advantages (e.g. Birkinshaw *et al.* 1998, Kuemmerle 1999, Andersson *et al.* 2002, Bathelt *et al.* 2004, Narula and Zanfei 2004, Cantwell and Mudambi 2005).

Table 10 Changes to learning mechanisms in the gradual progression from experimental development to applied research in Novozymes

Features of individual learning mechanisms	Variety: absent, emergent or present		Intensity: intermittent or continuous		Functioning: poor, moderate or good	
	2007–2011	2012–2016	2007–2011	2012–2016	2007–2011	2012–2016
Appropriation of knowledge based on STI mode of learning:						
1. Experimentation and testing	emergent	*present*	intermittent	*continuous*	moderate	*good*
2. External research collaborations	emergent	*present*	intermittent	*continuous*	poor	poor
3. Hiring experienced managers and scientists	emergent	*present*	continuous	continuous	good	*moderate*
Application of knowledge based on the DUI mode of learning:						
4. Practical technical problem-solving	present	present	continuous	continuous	good	good
5. Interaction with customers and suppliers	present	present	intermittent	*continuous*	moderate	*good*
6. Internal training and development	present	present	continuous	continuous	good	good

Identified changes to the variety, intensity, and functioning of individual learning mechanisms over the period from experimental development (2007-2011) to applied research (2012-2016) are italicised.

4.8 Unpacking the intra-organisational dimension concerning the interplay between science and engineering in innovation capability building

This chapter adopts a perspective based on the STI and DUI modes of learning to analyse empirically the innovation capability building process of Novozymes. Based on cross-sectional designs and econometric analysis drawn from statistics and survey samples, previous research has emphasised the positive relationship between the STI and DUI modes of learning on firm-level innovative performance. However, although rich in conceptual and empirical approaches, previous studies provide only limited evidence on the relative importance of the STI and DUI modes of learning and how changes to this relationship influence firm-level innovation capability building. This chapter goes beyond by suggesting how firms use the science-based and experience-based learning modes to implement innovative activities from a micro-level perspective. In doing so, the study draws on the concept of knowledge base and introduces conceptual elements that: (1) captured changes the relationship between the STI and DUI modes of learning, (2) assessed processes of interactive learning that influenced the gradual progression from intermediate to advanced innovative capabilities in Novozymes to develop enzyme technology for second-generation bioethanol production. It was found that during the period between 2007 and 2011, innovative capabilities were built mainly from practical technical problem-solving and user-producer interactions in the Brazilian innovation system, whereas during the period of applied research between 2012 and 2016, science-based learning gained importance relative to experience-based learning, mainly through improved testing and experimentation in the research laboratories.

It may be said that previous research on firm-level innovation capability building have tended to focus on the relative importance of internally and externally mediated learning mechanisms, thus overlooking the intra-organisational dimension concerning the interplay between science and engineering. The framework presented in this chapter does not claim to represent a final, comprehensive view of interactive learning, but it does take steps toward an understanding of the role of science and experience-based learning modes in firm-level innovation capability building. Hence, a focus on the relationship between the STI and DUI modes of learning in latecomer firms helps expose some of the qualitative discontinuities involved in innovation capability building. First, a focus on interactive learning directs attention away from a singular focus on science, technology and innovation relationships as the sole contributor to innovation and technological change and accentuates the importance of design and engineering-based activities. Relying on a single mode of learning based on individual learning mechanisms is unlikely to yield effective firm-level innovation capability building. Put differently; the analysis shows how processes of interactive learning are intertwined and need to be pursued in parallel.

Second, and reiterating here the central message of Jensen *et al.* 2007 about the making the two learning modes work together, the findings of this study give empirical support to go beyond focussing on appropriation and application as two separate processes, an ambiguity which obscures rather than reveals the exact nature of interactive learning. Rather, the science-based and experience-based learning modes can be viewed from a co-evolutionary perspective in the sense that learning and experience are derived from the balance and complementarity between the two. In the case of Novozymes, the experience-based mode of learning encountered in user-producer interaction during the early phase of experimental development constituted a logical sequence for the accumulation of the knowledge base that provided the scientists and engineers with a sense of opportunity and potential of Cellic CTec. The build-up of a minimum base of knowledge in bioethanol production, in turn, allowed Novozymes to develop more accurate simulations in the research laboratories and to gain a better understanding of enzymatic hydrolysis with respect to the different production stages. Hence, science-based learning gained relative importance, as the R&D department needed to appropriate the knowledge necessary to anticipate a variety of application conditions and to understand the relevant parameters influencing the different stages of bioethanol production. Therefore, a deliberate effort was made to determine new methods of developing customer-specific solutions based on local market conditions and raw material characteristics. In this way, it was the balance and complementarity science-based and experience-based learning mechanisms and the intensity with which these were pursued, that influenced the gradual progression from intermediate to advanced innovative capabilities in Novozymes.

In this way, this chapter contributes to moving beyond the prevailing understanding by drawing attention to the process whereby a latecomer firm orchestrated processes of interactive learning derived from the interplay between science and engineering to create and accumulate capabilities to innovate. Nevertheless, further research across different industries is needed to address the relationship between the STI and DUI modes of learning as part of the process of building innovative capabilities in latecomer firms. In particular, this chapter only implicitly considered the role and function of Novozymes as a subsidiary in the corporate network of a multinational company and how the increasing offshoring and outsourcing of R&D activities to developing countries influence firm-level innovation capability building. Considering the changing geography of innovation imposed by globalisation, there is a need to understand better how the appropriation and application of knowledge work across interrelated spatial scales and how the formation of global innovation networks may work connect and enhance processes of interactive learning between and across national innovation systems. This is a central research objective that is explored in the next chapter of the thesis.

5. Enhancing international technology cooperation to address climate change: The role and function of innovation intermediaries in global innovation networks

The previous chapter developed an understanding of how Novozymes created and accumulated the capabilities needed to manage innovation in industrial enzyme technology for second-generation bioethanol production in Brazil. It explored how changes to the relationship between the science-based and experience-based learning modes influenced the upper levels of innovative capability as the subsidiary over a 10-year period progressed from intermediate to advanced levels and how these interactive learning processes were conditioned by the Brazilian innovation system.

National innovation systems studies have long argued that networks of actors and institutions situated around local knowledge bases intensify interactive learning and innovation. In this chapter, this view of interactive learning and innovation as spatially bounded phenomena is challenged, as it is increasingly recognised that these processes may be organised and work between and across interrelated spatial scales independently of any geographical limitations (Coenen *et al.* 2012). Recent empirical studies, mapping the spatial patterns of innovation suggest that the formation of global innovation networks spanning national innovation systems complements the development and diffusion of knowledge (see for instance Binz *et al.* 2014, Gosens *et al.* 2015, Wieczorek *et al.* 2015). A network view of innovation that transcends the effects of distance, in turn, raises interesting questions about other forms of proximity as a sufficient condition for interactive learning and innovation processes. Fully understanding this dynamic calls for an integrative view in which established innovation system concepts are linked to the changing geography of innovation.

Moreover, over the past decades, numerous international cooperative initiatives have emerged, forming global innovation networks between locally situated actors and organisations engaged in the development and diffusion of knowledge and environmentally sound technologies.[47] At the same time, however, it is widely recognised that international technology cooperation is contingent on actors and organisations having the innovative capabilities needed to effectively optimise and adapt technology transferred to local conditions (e.g. Fu *et al.* 2011, Bell 2012). Innovation capability building involves the combination of different modes of learning and forms of knowledge; that is, interactive learning and capacity building processes conditioned by national innovation systems, which in developing countries are often fragmented and emerging. However, considering the changing geography of innovation, the formation of global innovation networks may be understood as a compensatory mechanism for locally situated actors to access

[47] Environmentally sound technologies are distinctive in that they encompass the potential for improved environmental performance relative to other technologies and thus form an important part of the solution to address the challenge of climate change (see for instance Rennings 2000, Stern 2007). In this chapter, 'environmentally sound technologies' are hereafter referred to as 'technologies' unless otherwise noted.

external knowledge and experience that are not readily available in their national innovation system. This chapter furthers the understanding of how the formation of global innovation networks may work to enhance processes of interactive learning in national innovation systems and in what way international technology cooperation complements the creation and accumulation of capabilities needed to manage innovation and technological change in developing countries.

The chapter is guided by the following research questions: (1) how does the formation of global innovation networks enhance processes of interactive learning in national innovation system to complement the development of innovation capabilities in developing countries, and (2) what are the role and function of innovation intermediaries in this dynamic? The remainder of the chapter is organised as follows. Section 1 reviews and discusses three knowledge-based perspectives on the globalisation of innovation. Drawing on the strategic management literature and recent insights from economic geography, section 2 develops a framework that differentiates between forms of global innovation networks. Section 3 connects interactive learning processes in global innovation networks to innovation capability formation in national innovation systems and discusses the role and function of innovation intermediaries in this dynamic. Section 4 presents the empirical setting while section 5 outlines the methodology for the empirical part of the chapter, Section 6 probes two innovation intermediaries (1) Climate Technology Centre and Network of the United Nations Framework Convention on Climate Change and (2) International Energy Agency Technology Collaboration Programmes, while section 7 maps broader the landscape of international technology cooperation in the context of climate change. Section 8 concludes the chapter and discusses policy implications for international technology cooperation.

5.1 Globalisation of innovation

The analytical limit of innovation systems studies to particular spatial scales seems increasingly less appropriate considering the changing geography of innovation. Innovation scholars are calling that the globalisation of innovation is clarified to develop more accurate interpretations of contemporary innovation processes (see for instance Grillitsch and Trippl 2014, Martin 2016, Weber and Truffer 2017). Before proceeding to discuss the features of global innovation networks, it is important to clarify here that the established literature on national innovation systems generally views interactive learning and innovation as spatially bounded processes.[48] This is not least due to the tacit nature of knowledge that in contrast to explicit knowledge is sticky and difficult to appropriate by means of codification (von Hippel 1994). In other words, it is simpler to diffuse

[48] For instance, Lundvall defines a national innovation system as 'the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge ... and are either located within or rooted inside the borders of a nation state' (1992:3).

tacit knowledge over short distances, while the positive externalities become less intense and often costlier the larger the distance (Jaffe *et al.* 1993). In addition, a shared social, economic, and institutional context is emphasised in the literature as enabling factors for innovation (Patel and Pavitt 1994). Therefore, interactive learning between users and producers of innovation is suggested to benefit from co-location in the learning economy (Lundvall and Johnson 1994).

This chapter suggests that the national innovation systems concept fails to fully incorporate the rapidly changing geography of innovation imposed by globalisation. In particular, the explicit focus on spatial scales fails to capture the opportunities for interactive learning that national innovation systems gain from external knowledge linkages. A central proposition of this research is that processes of interactive learning are increasingly enacted through the formation of global innovation networks spanning national innovation systems. The onset of the information age associated with the spread of information and communications technology is a key factor explaining this dynamic change. The advance of massive digital network infrastructure, online platforms, and knowledge management systems has fundamentally altered the interdependencies of innovation (OECD 2008). In this way, the conventional tacit-explicit dichotomy of knowledge described as the determinant for interactive learning and innovation in much of the earlier literature is becoming increasingly blurred (see also Liu *et al.* 2013, Grillitsch and Trippl 2014). The main argument here is that spatial proximity may neither be a necessary nor sufficient condition for the development and diffusion of knowledge, as other forms of proximity may substitute and complement processes of interactive learning and innovation (Boschma 2005).

The surge of global innovation networks can give the impression that a perspective on national innovation systems is no longer relevant, but the author argues against this view. Rather, a dynamic is proposed where the formation of global innovation networks may work to connect and enhance processes of interactive learning between and across national innovation systems. Hence, as illustrated in Figure 5, the focus of the chapter is this dynamic of enhancing processes of interactive learning through the formation of global innovation networks spanning national innovation systems.[49] The existing literature on the globalisation of innovation supports this more dynamic view of interactive learning and innovation (e.g. Archibugi and Michie 1995, Archibugi *et al.* 1999). Furthermore, recent studies on regional innovation systems have started to reveal a more nuanced picture of innovation processes accruing in various ways across space and scale (e.g. Asheim and Isaksen 2002, Asheim and Coenen 2005, Rodríguez-Pose and Crescenzi 2008). Likewise, empirical work on industrial clusters often questions the orthodoxy that

[49] The conceptualisation of global innovation networks proposed in this chapter complements the framing of global innovation systems recently proposed in Binz and Truffer (2017).

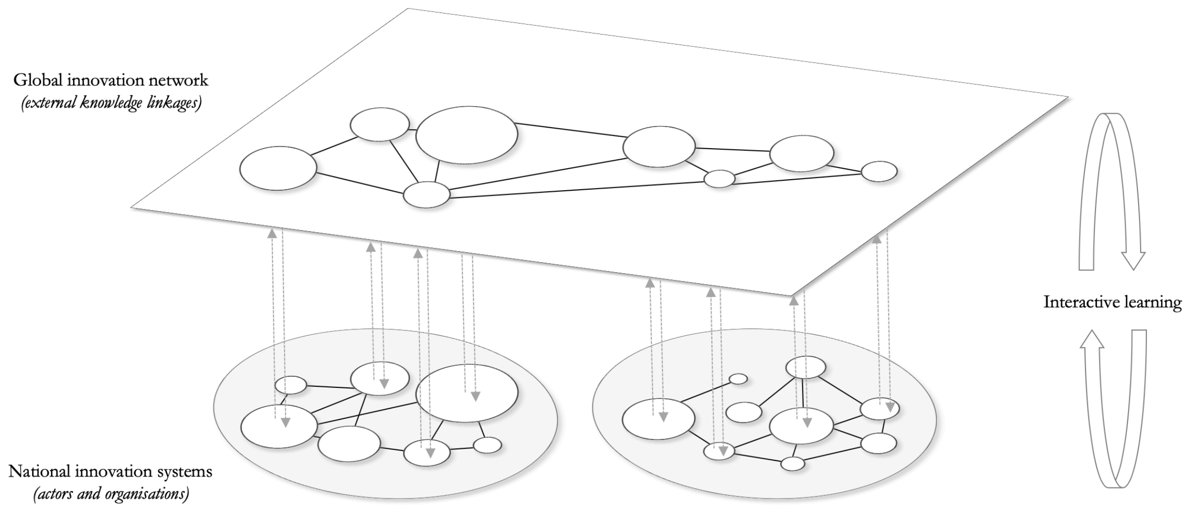

Figure 5 Formation of global innovation networks spanning national innovation systems

knowledge development and diffusion are exclusively local processes (e.g. Spencer 2003, Bathelt *et al.* 2004, Giuliani and Bell 2005). Besides, a small subset of the literature on sustainability transitions focuses on contemporary global dynamics and the increasing interdependencies of innovation across space and scale (e.g. Markard *et al.* 2012, Hansen and Coenen 2015, Truffer and Battistini 2015). The picture emerging from these different pieces of literature is a scalar dynamic, where locally situated actors may use global innovation networks as a compensatory mechanism to access external knowledge and experience not readily available in their national innovation systems. However, despite the obvious development potential of exploiting global innovation networks as a strategic mean to complement innovation capability accumulation in developing countries, with notable exceptions (see for instance Chaminade and Vang 2008, Figueiredo 2011, Liu *et al.* 2013, Giuliani *et al.* 2014, Barnard and Chaminade 2017, Haakonsson and Slepniov 2018), few studies have analysed this phenomenon. Before conceptualising different forms of global innovation networks, three knowledge-based perspectives particularly attentive to the globalisation of innovation are briefly introduced and discussed. These knowledge-based perspectives characterise innovation processes, which subject to the mode of learning and form of knowledge, may organise and work between and across national innovation systems Table 11 summarises the global dimension of innovation based on three features of knowledge: (1) source of knowledge, (2) diffusion of knowledge, (3) knowledge linkages.

5.1.1 Local buzz and global pipelines

The contribution of Bathelt *et al.* (2004) on local buzz and global pipelines figures prominently in current debates on the globalisation of innovation. Local buzz refers to the relatively free association and seamless participation in the development and diffusion of knowledge in industrial clusters, whereas global pipelines are deliberately established connections to distant sources of knowledge. The establishment of global pipelines rests on purposive and planned efforts of firms and industries and is considered more risky and costly than local buzz. Bathelt *et al.* (2004) claim that firms embedded in clusters and maintaining high levels of local buzz, while creating access to external knowledge through global pipelines, demonstrate relatively higher levels of innovative activity and dynamism (see also Morrison *et al.* 2012). Global pipelines and local buzz are, therefore, viewed as complementary processes for interactive learning and innovation. The local buzz and global pipelines approach has been criticised for a number of reasons. A critical shortcoming is that this perspective tends to conflate local buzz with seamless participation, while paying little attention to the presence of innovation capabilities as an essential precondition for building the capacities necessary to absorb the knowledge developed and diffused through global pipelines (see for instance Moodysson 2008).

5.1.2 Knowledge bases in firms and industries

Asheim and Coenen (2005) extend the debate on the globalisation of innovation based on their differentiation of knowledge bases in firms and industries. The concept of knowledge bases in the economic geography literature typically distinguishes between three forms of knowledge: (1) analytical, (2) synthetic, (3) symbolic. Synthetic knowledge has a strong tacit component that differs from place to place, while analytic knowledge is more explicit in nature. Firms and industries dominated by analytical knowledge bases often tap into geographically dispersed sources of knowledge, whereas those dominated by synthetic knowledge bases typically exchange knowledge with customers and suppliers that are geographically close. Therefore, there is general agreement in the literature that industries relying on synthetic knowledge tend to operate locally, whereas industries operating based on analytic knowledge are more global (Asheim and Gertler 2006). In contrast to analytical and synthetic knowledge, symbolic knowledge is highly tacit and generally have meaning only in specific contexts. To summarise, economic geography studies suggest that the degree to which firms and industries become more or less globalised is highly contingent on the underlying knowledge base (see also Morrison 2008, Manniche 2012, Martin 2013).

5.1.3 Business innovation modes

As discussed in the previous chapter, the contribution of Jensen *et al.* (2007) draws attention to the forms of knowledge and modes of learning that influence interactive learning in firms and industries. The authors differentiate two complementary modes of learning and innovation:

STI and DUI. Numerous studies have since emphasised the relationship between the STI and DUI modes of learning and how it contributes to firm-level innovation performance. Regarding the nature of knowledge, Jensen *et al.* (2007) distinguish between local and global forms as well as types of knowledge. Explicit knowledge is related to know-why, whereas tacit knowledge is more related to know-how. All forms and types of knowledge matter for interactive learning and innovation; however, their relative importance differs between the STI and DUI modes of learning. The STI mode of learning relies more on global and explicit knowledge, emphasising scientific methods and principles with a focus on understanding and interpretation. The DUI mode of learning depends more on local and tacit knowledge, wherein user-producer interaction and problem-solving play essential roles.

5.2 Global innovation networks

Drawing on these three knowledge-based perspectives, we now discuss how and in what way the formation of global innovation networks may work to enhance processes of interactive learning in national innovation systems. However, despite the growing number of studies in this area, there is still a lack of consensus on how to treat and conceptualise global innovation networks both in theoretical and empirical terms (see for instance Liu *et al.* 2013, Herstad *et al.* 2014, Chaminade and Plechero 2015, Haakonsson and Ujjual 2015, Barnard and Chaminade 2017). Two preliminary points are important here before explaining the features of global innovation networks.

Table 11 Knowledge-based perspectives on the globalisation of innovation

	Source of knowledge:	Diffusion of knowledge:	Knowledge linkages:
Local buzz and global pipelines	Not explicitly discussed	Diffusion explained by complementary knowledge flows: Local buzz: local Global pipelines: global	Distinction between informal (local buzz) and formal (global pipelines) linkages of external knowledge
Knowledge bases in firms and industries	Dominant sources of knowledge: (i) analytical: mainly developed from basic and applied research (ii) synthetic: mainly developed from user-producer interaction (iii) symbolic: project dependent	Diffusion is described according to the dominant knowledge bases in firms and industries: (i) analytical: mainly global (ii) synthetic: national and regional (iii) symbolic: local	(i) analytical: R&D collaboration (ii) synthetic: learning and experience gained through formal and informal user-producer interaction (iii) symbolic: project groups
Business innovation modes	Knowledge is developed from interactive learning processes characterised by the balance between the STI and DUI modes of learning	Diffusion is explained by types (explicit & tacit) and forms (know-why & know-how) of knowledge: STI: global – explicit – know-why DUI: local – tacit – know-how	STI: scientific methods and principles with a focus on understanding and interpreting DUI: problem-solving based on user-producer interaction

Based on Bathelt et al. (2004), Asheim and Coenen (2005), and Jensen et al. (2007)

First, this research is based on a knowledge-based perspective in the sense that the development and diffusion of knowledge are viewed as essential means for interactive learning and innovation. Second, the locus of innovation does not reside exclusively with the individual system components of national innovation systems but as processes of interactive learning enacted through networks between different actors and organisations operating under a particular institutional setting. It is suggested that innovation systems scholars must start to clearly and precisely articulate these processes of interactive learning and recognise that these may be embedded in innovation networks that transcend conventional innovation system boundaries. Following Coe and Bunnell, a central premise of this chapter is that 'one should make no a priori presumptions as to how the configurations of network relations that constitute an innovation system are spatially bounded' (2003:439). Hence, in this research, global innovation networks are broadly defined as follows:

Box 3 Global innovation network *(working definition)*

Global innovation networks are networks spanning national innovation systems that engage actors and organisations in processes of interactive learning related to and resulting in innovation.

In what follows, the STI and DUI modes of learning are separated from their organisational form, as processes of interactive learning in global innovation networks are determined from combinations of the two. Drawing on the strategic management literature, and in particular the contribution of Holmqvist (2004), the following subsections seek to develop a conceptual framework that differentiates between forms of global innovation networks along two key dimensions: (1) modes of learning, (2) organisational form. These two dimensions are described in more detail in the following.

5.2.1 Modes of learning

As the development and diffusion of knowledge are considered the means for interactive learning, it is essential to clarify the bases of these processes. To this end, the chapter distinguishes between interactive learning derived from the *exploration* and *exploitation* of knowledge. This distinction is based on the seminal work of March (1991), which has come to dominate the debate on organisational learning and innovation. A large body of research in strategic management has since probed the interplay between exploration and exploitation of knowledge in organisational learning and innovation (see for instance McGrath 2001, Katila and Ahuja 2002, Benner and Tushman 2003, Siggelkow and Levinthal 2003, He and Wong 2004, Holmqvist 2004). As proposed by March: 'the essence of exploitation is the refinement and extension of existing competences, technologies, and paradigms … [whereas] the essence of exploration is experimentation with new alternatives' (1991:85).[50] Levinthal and March clarify this distinction, elaborating that the rationale for exploration involves, 'a pursuit of new knowledge, of things that might come to be known … [whereas the exploitation of knowledge relates to] the use and development of things already known' (1993:105). Based on this evolutionary approach to organisational learning and innovation, Benner and Tushman (2003) suggest that exploitative innovation involves incremental improvements and builds on current technological trajectories, whereas exploratory innovation involves shifts to new and changing trajectories. Similarly, Gupta *et al.* (2006) note that the difference between exploration and exploitation of knowledge pertain to whether learning occurs along the same trajectory or a new and different trajectory. An organisation may pursue exploration and exploitation of knowledge across multiple domains. However, within a single domain, the interplay between the two often competes for organisational resources. Here, 'choices must be made between gaining new information about alternatives and thus improving future returns (which suggests allocating part of the investment to searching among uncertain alternatives), and using the information currently available to improve present returns' (March 1991:72). Hence, as argued by Nelson and Winter, the principal means by which an organisation contributes to the exploration of knowledge is the emanation of queries generated by dissatisfaction with the current technological trajectory: 'one way in which the routine functioning of an organization can contribute to the emergence of innovation is that useful questions arise in the form of puzzles or anomalies relating to prevailing routines' (1982:129). Although it is generally agreed that exploration and exploitation of knowledge in single domains are mutually exclusive, the need to balance the two across multiple domains is well established (see for instance Marengo 1993, Eisenhardt and Martin 2000, Gibson and Birkinshaw 2004). To explore the internal organisation of capabilities to manage the balance between exploration and exploitation in organisational learning and innovation, the previous chapter operationalised interactive learning as two distinct but intertwined processes of appropriation and application. Appropriation relates mainly to the STI mode of innovation, where learning and experience are gained from the exploration of knowledge based on features such as search and experimentation. On the other hand, application relates mainly to the DUI mode of innovation, where learning and experience are gained from the exploitation of knowledge, wherein features such as modification and implementation played important roles. Table 12 summarises the division of modes of learning in global innovation networks categorised by the ideal types of exploration and exploitation.

[50] See also the extensive reviews by Gupta *et al.* (2006), Li *et al.* (2008), and Lavie *et al.* (2010), which draw together the existing empirical evidence on the interplay between the exploration and exploitation of knowledge in organisational learning and innovation.

Table 12 Modes of learning in global innovation networks

	Exploration:	Exploitation:
Rationale	Development of new knowledge	Diffusion of existing knowledge
Technological change	Discontinuity in technological trajectory	Continuity in technological trajectory
Business innovation mode	Science, technology and innovation (STI)	Doing, using and interacting (DUI)

Based on Dosi (1982), March (1991), Holmqvist (2004), and Jensen (2007)

5.2.2 Organisational form

The knowledge and experience derived from the formation of global innovation network must be effectively integrated into organisations. Following Holmqvist (2004), this integration takes place in networks within and between organisations. Put differently, the exploration and exploitation of knowledge in global innovation networks may take both *intraorganisational* and *interorganisational* forms. The formation of intraorganisational networks spanning national innovation systems is mainly concerned with interactive learning in single organisations (multinational corporations, for instance, as described in the previous chapter), where the exploration and exploitation of knowledge takes place internally within groups, departments, and facilities (e.g. Kogut and Zander 1992, Nonaka and Takeuchi 1995, Argote and Ingram 2000, Gupta and Govindarajan 2000). On the other hand, interorganisational networks spanning national innovation systems refer to interactive learning achieved through the cooperation of multiple organisations in strategic alliances or other forms of arrangements (e.g. Powell *et al.* 1996, McEvily and Zaheer 1999, Gulati *et al.* 2000, Zollo *et al.* 2002). Following Holmqvist (2004), the interplay between the exploration and exploitation of knowledge in intraorganisational networks that generate external knowledge linkages between and across multiple organisations is referred to as extension. Hence, extension concerns processes whereby a single organisation extends its knowledge and experience in global innovation networks to other actors and organisations (Hamel 1991). On the other hand, the combination of knowledge and experience gained from interactive learning in interorganisational networks between multiple organisations is referred to as internalisation (Larsson *et al.* 1998). In sum, through the formation of global innovation networks, an organisation may extend its knowledge and experience by cooperating with organisations across national innovation systems. Moreover, single organisations can cooperate to internalise collectively created knowledge and experience between multiple organisations across national innovation systems. Extension and internalisation through external knowledge linkages spanning national innovation systems can be considered the main reason for the formation of global innovation networks (see also Figure 5). On one the hand, the purpose is to internalise collectively created knowledge and experience, while on the other hand, organisations may extend their knowledge and experience to engage in new collective explorative and exploitative undertakings. Hence, interactive learning in global innovation networks may refer to the exploration and exploitation of knowledge in intraorganisational networks (a single organisation embedded in multiple national innovation systems) and to interorganisational networks forming between and across multiple organisations. Table 13 summarises this division between global innovation networks categorised according to intraorganisational and interorganisational forms.

Table 13 Organisation of global innovation networks

	Intraorganisational	Interorganisational
Network	Across a single organisation	Between and across multiple organisations
Collaboration	Informal/internal network relationships	Formal strategic alliances/contractual arrangements
Learning process	Extend knowledge and experience	Internalise knowledge and experience

Based on Powell et al. (1996), Gupta and Govindarajan (2000), and Holmqvist (2004)

5.2.3 Framework for global innovation networks

Plotting the two dimensions against each other enables the creation of a simple framework for interactive learning in global innovation networks, as presented in Figure 6. It must be emphasised that the framework is meant as a heuristic device and the demarcation in and between the two dimensions are ideal types. The application of the framework does not imply that different forms of global innovation networks can be differentiated and precisely positioned along the two axes; rather, they can be compared relative to each other. As will be shown in later parts of the chapter, this type of categorisation has intrinsic value. It brings to light how interactive learning is derived from the exploration or exploitation of knowledge and whether these processes are based on intraorganisational or interorganisational network arrangements. Based on this understanding, this chapter broadly defines international technology cooperation as follows:

Box 4 International technology cooperation *(working definition)*

International technology cooperation is viewed as interactive learning processes between multiple actors engaged in the exploration and/or exploitation of knowledge through the formation of global innovation networks.

The next section proceeds by proposing a model for how international technology cooperation complements the formation of innovation capabilities in developing countries. Among others, this builds on recent policy proposals for 'Climate Innovation Centres' by Sagar (2009) and 'Climate Relevant Innovation-system Builders' by Ockwell and Byrne (2016).

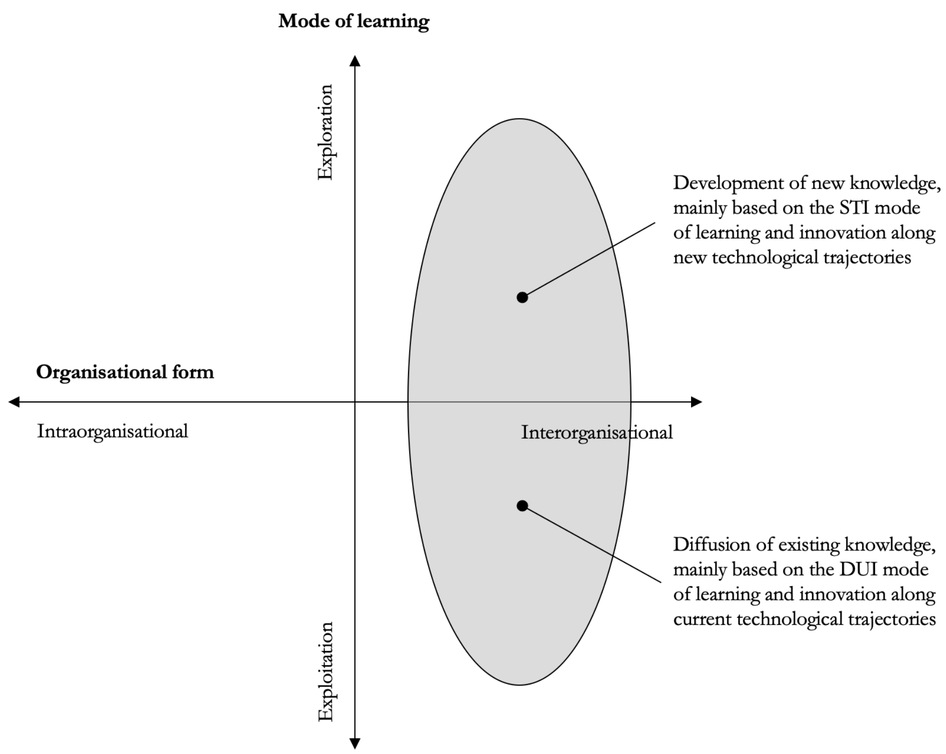

Figure 6 Framework for interactive learning in global innovation networks

5.3 Formation of innovation capabilities

The interplay between the exploitation and exploration of knowledge in global innovation networks elucidates a key feature of interactive learning. Knowledge and experience derived from global innovation networks do not occur automatically but require deliberate and continuous efforts to improve interactive learning. This dynamism is inherently contingent on actors and organisations in national innovation systems having the necessary innovative capabilities needed to effectively optimise and adapt technology to local conditions. To understand the internal organisation of capabilities needed to manage the exploration and exploitation of knowledge in global innovation networks, we refer to the distinction between production and innovation capabilities in latecomer firms (e.g. Lall 1992, Bell and Pavitt 1995, Hobday 1995, Figueiredo 2002). Although the boundary between the two is blurred in practice, the distinction is important and has provided a more nuanced understanding of technological catch-up. The former is mainly concerned with the knowledge and experience needed to *operate* and *maintain* technology in production systems, while the latter refers to the knowledge and experience employed to *manage* innovation and technological change (the review by Bell and Figueiredo (2012) crystallises the existing empirical evidence on the manner and rate at which latecomer firms create and deepen innovation capabilities alongside their production capabilities).

As described in the previous chapter, the literature on technological capabilities has generated various framework of classifying 'levels' or increasing 'depths' of creative engagement with technology in latecomer firms (see for instance Lall 1992, Bell and Pavitt 1995, Figueiredo 2002). Such classifications have been successfully applied in empirical studies across a wide variety of industries and countries. Later studies have used different approaches, varying terms, and concepts but have all inferred that different levels of capability lie behind the different types of technological activity in latecomer firms (e.g. Chuang and Hobday 2013, Lema *et al.* 2015, Lee and Malerba 2017, Hansen and Lema 2019, Figueiredo and Cohen 2019). This process of accumulating deeper and broader stocks of knowledge to manage innovation and technological change in latecomer firms is generally referred to as innovation capability building.

5.3.1 Knowledge and experience derived from global innovation networks

In the context of this chapter, the term innovation capability building is used more broadly, covering not only firms but essentially all actors and organisations listed in Table 2. It refers to the process in which external knowledge is appropriated and applied in innovation and technological change. This circular dynamic consists of three interrelated elements: (1) absorptive capacity, (2) interactive learning, (3) innovation capabilities. Absorptive capacity refers to the ability of actors and organisations to recognise the value of external knowledge and appropriate and apply it in innovative activities. Interactive learning refers to the internal organisation of capabilities to accumulate deeper and broader stocks of knowledge, a dynamic derived from the balance between the interplay between the STI and DUI modes of learning. Innovative capabilities are built from the combination of absorptive capacity and interactive learning. This dynamism may accrue or diminish over time depending on the extent to which deliberate and continuous efforts are made to sustain it. The internal organisation of capabilities to appropriate and apply knowledge in innovation and technological change precipitates that actors and have the absorptive capacity and prior knowledge bases necessary to effectively internalise external knowledge end experiences.

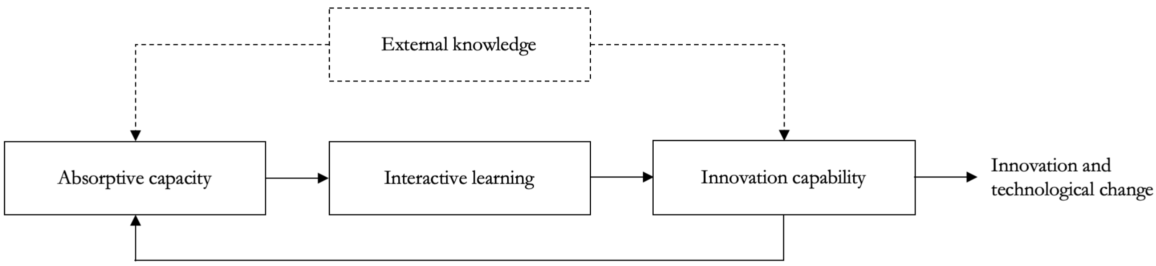

Figure 7 Knowledge and experience derived from global innovation networks

It is acknowledged that the process captured in Figure 7 is a simplification that scarcely does justice to the inevitable deviations and qualitative discontinuities in innovation capability building. Nevertheless, for this chapter, a stylised representation is useful for considering how external knowledge and experience derived from the formation of global innovation networks complement innovation capability building.[51] In this way, the exploration and exploitation of knowledge in global innovation networks may contribute to strengthening the prior knowledge base of actors organisations and may contribute to a deepening of innovation capabilities through the subsequent use of technology that extends beyond merely routine operations to enable a series of cumulative innovation and technological change. Against this background, international technology cooperation – as defined in Box 4 – may generate three qualitatively different flows of knowledge and experience (see also Ockwell *et al.* 2008, Bell 2012, Lema and Lema 2012, Watson *et al.* 2014).

1. *Capital goods such as machinery, equipment, and related engineering services.* This flow consists of tangible assets and bundles of explicit and codified knowledge, such as 'ready-made' designs, technical models, and blueprints. This first flow of external knowledge and experience may also be considered as paper-embodied technology, which can be purchased or licensed.
2. *Various skills and knowledge for operating and maintaining technology.* This flow consists of intangible assets and tacit knowledge. This second flow of knowledge and experience may be considered as disembodied technology, which arrives in the form of human and knowledge capital.
3. *Knowledge and experience for managing and changing technology.* This flow consists of intangible human capital; however, in contrast to the second flow, also includes organisational assets to manage innovation and technological change. This third flow can be further delineated as delivering and creating people-embodied technology in the form of external knowledge and experience needed to optimise and adapt the technology initially acquired.

To summarise, the first two flows may deliver new or improved production capabilities. However, alone, they do little or nothing for the development of innovative capabilities needed to manage innovation and technological change. Based on the premise that the presence of innovation capabilities in developing countries is an essential prerequisite to effectively optimise and adapt technology to local conditions, it is essential that international technology cooperation captures all three flows of external knowledge and experience.

[51] Kim (1998) provides a useful way to understand how the interaction between appropriation and application of knowledge is organised through successive cycles of interactive learning, consisting of four key activities: (1) internal preparation for the appropriation of external knowledge, (2) the appropriation of external knowledge, (3) its effective application in innovation and technological change, (4) its subsequent improvement creating a higher knowledge base (see also Leonard-Barton 1995, Nonaka and Takeuchi 1995).

5.3.2. Role and function of innovation intermediaries

This section proceeds to consider the role and function of innovation intermediaries in global innovation networks and their contribution to enhancing interactive learning in national innovation systems. Nevertheless, the multifaceted literature on innovation intermediaries, which has emerged over the last decades is far from unified. There is a lack of clarity on how innovation intermediation is defined and where it begins and where it ends. For instance, in an extensive literature review, Howells (2006) identifies the following ten functions of innovation intermediaries: foresight and diagnostics, scanning and information processing, knowledge processing and combination/recombination, gatekeeping and brokering, testing and validation, accreditation, validation and regulation, protecting the results, commercialisation, and evaluation of outcomes. Categorisations and typologies of innovation intermediaries vary among the key contributions and partly overlap. [52] As pointed out by Kivimaa *et al.* (2019), which focuses on the role and function of in intermediaries in sustainability transitions, empirical evidence is lacking on what makes innovation intermediation effective in compensating for market and systemic failures, and assessing the impact of innovation intermediaries in absolute terms is challenging given their indirect effects on innovation processes (see also Kivimaa 2014).

A widely used definition describes an innovation intermediary as 'an organization or body that acts as an agent or broker in any aspect of the innovation process between two or more parties' (Howells 2006:720). Innovation intermediaries have been found to emerge in response to weak or missing linkages between the individual system components of innovation systems (Muller and Zenker 2001). For instance, den Hertog (2000) describes the role of innovation intermediaries as facilitators of innovation that engage in network brokering and innovation system (re)configuration activities. However, the notion of 'facilitator' is somewhat ambiguous, as innovation intermediaries are often not restricted to this role, but take on other functions, such as the combination or recombination of knowledge or to cover more traditional research, financial, and technical services (Boon *et al.* 2011). In this way, Klerkx and Leeuwis perceive innovation intermediaries as 'facilitators of innovation', engaging is network and innovation system-building activities, and group the functions of these into three broad categories: (1) demand articulation, (2) network formation, (3) innovation process management (2009:851). Hence, innovation intermediaries contribute to several of the innovation systems functions described by Hekkert *et al. (*2007) and Bergek (2008), notably knowledge diffusion through networks, guidance of the

[52] 'Innovation intermediary' is an umbrella term covering a range of actors and organisations including 'third parties' (Mantel and Rosegger 1987), 'intermediary firms' (Stankiewicz 1995), 'knowledge-intensive business service firms' (Den Hertog 2000), 'bridging organisations' (Bessant and Rush 1995), 'technology and knowledge brokers' (Hargadon and Sutton 1997), 'information and technology transfer intermediaries' (Popp 2000), 'superstructure organisations' (Lynn *et al.* 1996), and 'innovation brokers' (Winch and Courtney 2007).

search, and resources mobilisation. Therefore, innovation intermediaries may be understood to complement and create interdependencies with each other but also compete and leave gaps in terms of managing various stages of the innovation processes (Klerkx and Aarts 2013).

A particular type of innovation intermediary – the focus in this chapter – can be referred to as an innovation broker (Winch and Courtney 2007). An innovation broker is neither responsible for the development nor the diffusion of knowledge but for enabling actors and organisations in innovation systems to innovate (van Lente *et al.* 2003). Previous empirical studies highlight that the central premise for innovation brokers is their impartial and independent position in innovation systems (Kolodny *et al.* 2001). In other words, innovation brokers facilitate innovation as their core function, distinguishing them from other types of innovation intermediaries more aptly described as developers or users of innovation (Stewart and Hyysalo 2008). Innovation brokers typically work on a non-profit basis and are often organised as public-private partnerships. It has been found that resource dependencies may result in bias in innovation process management, as these may force innovation brokers to exercise topical steering in their demand articulation. Such steering by policy or procurement objectives threaten the impartiality of innovation brokers, and it may give rise to a dilemma in which the fulfilment of particular interests of funding bodies and other special interests are given primacy (Klerkx and Leeuwis 2008).

Innovation brokers work as a systemic instrument for public policy intervention, where governments combine both supply and demand-side measures to exercise their role as mediators in innovation systems (Kivimaa 2014). Klerkx and Leeuwis (2009) present the following reasons as to why governments have an interest in coordinating the functions of innovation systems through the delegation of authority to innovation brokers, such as quasi-autonomous agencies or government-initiated foundations: (1) it is often difficult to make the basic functions of demand articulation in innovation networks self-sufficient, (2) innovation brokers stimulate interaction at the innovation system level, (3) innovation brokers can more neutrally fulfil the role of innovation 'facilitator' than organisations more aptly described as developers and users of innovation.

This brief review has highlighted the particular type of innovation intermediary dedicated to facilitating innovation through the brokerage of networks from an impartial and independent position. At the systemic level, innovation intermediaries work to strengthen the structural composition of the innovation system, creating networks and linkages between actors, supporting them in accessing a variety of tangible and intangible resources that are needed to enhance or optimise the innovation 'ecosystem'. At the level of interaction between the system components, innovation intermediaries act as interstices that guide innovation networks into formation by handling day-to-day network management issues while enhancing trust and resolving conflict.

5.4 Empirical setting: United Nations Framework Convention on Climate Change

Climate change threatens to impede economic development and cause irreversible damage to fragile ecosystems. Assessed by the Intergovernmental Panel on Climate Change (IPCC), intricate models to mitigate and adapt to the impacts of climate change are continually revised and refined as new data become available (IPCC 2014). The United Nations Environment Programme (UNEP) reports that greenhouse gas (GHG) emissions continue to rise to unprecedented levels. In agreement with IPCC, UNEP endorses the statement that to limit global warming to two degrees above pre-industrial levels, the level of annual GHG emissions in 2030 must be kept below 40 Gt of CO_2e. UNEP further estimates that in 2017, GHG emissions were at 53.5 Gt of CO_2e, and in a business-as-usual scenario, GHG emissions are on track for 59 Gt of CO_2e in 2030. This indicates a gap of at least 19 Gt of CO_2e to be closed before 2030 (UNEP 2018).

Achieving a stabilisation of GHG concentrations in the atmosphere that prevents dangerous anthropogenic interference with the climate system requires deep decarbonisation and a substantial reduction of GHG emissions (IPCC 2018). Developed countries cannot bridge the emission gap alone and developing countries will need to bear an increasingly larger share of the mitigation burden. However, developing countries face many pressing development challenges, and there is concern that enhanced climate action may compromise legitimate economic development objectives. For instance, as previously mentioned, the constantly growing but largely unmet energy needs of developing countries is projected to more than double over the next decades, which will significantly impede not only economic development but also progress towards attaining vital sustainable development objectives (see for instance IEA 2017).

The United Nations Framework Convention on Climate Change (UNFCCC) is a comprehensive policy framework mandated to prevent dangerous anthropogenic interference with the climate system. Structured around the principle of common but differentiated responsibilities and respective capabilities, the UNFCCC has over the last three decades framed the global effort and ambition to address climate change. Parties to the UNFCCC (member states) have since met annually in Conferences of the Parties (COP) to strengthen the global response to climate change.

The Kyoto Protocol, adopted at COP 3 in Japan in 1997, translated the UNFCCC mandate into legally binding emission reduction targets for developed countries and introduced a set of flexible mechanisms – (1) International Emissions Trading, (2) Joint Implementation, (3) Clean Development Mechanism – allowing these member states to exploit international economic opportunities to meet part of their obligations under the Convention. The first commitment period of the Kyoto Protocol started in 2008 and ended in 2012, while the second commitment period began in 2013 and will end in 2020. The Paris Agreement adopted at COP 21 in France in 2015 marks the latest step in the evolution of UNFCCC. The Paris Agreement seeks to accelerate and intensify the actions and investment needed to strengthen the policy response to climate change by keeping the global temperature rise this century well below two degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Notwithstanding the current political momentum, the continuous rise in GHG emissions attests to the difficulty of operationalising the mandate of the UNFCCC. Two causes of policy inertia are arguably that countries' contribution to climate change and their capacity to mitigate and adapt to its consequences vary significantly. Moreover, the risk that climate change poses for human and ecosystems are perceived and ranked differently given diverse values and goals. This is further complicated by competing and conflicting discourses and ethical approaches to environmental justice vis-à-vis economic development (see for instance Hulme 2009).[53]

5.4.1 Development and transfer of technology under the UNFCCC: a brief history

Since the establishment of the UNFCCC in 1992, member states have increasingly recognised and emphasised the need to enhance action on international technology cooperation. However, a key sticking point in the climate negotiations is the lack of consensus on how best to support the development and transfer of technology in developing countries. Most developed country parties favour an approach that promotes the development and transfer of technology through market-based solutions and enabling environments, whereas developing countries maintain that the formation of innovation capabilities is needed to achieve the objectives of the UNFCCC. Thus, consensus among member states on how best to undertake international technology cooperation has yet to be reached. It is beyond the scope of this chapter to recall all the provisions related to international technology cooperation made by the COP since the establishment of the UNFCCC. Only the most important decisions and outcomes are highlighted here. Against this background, negotiations related to international technology cooperation under the UNFCCC can be divided into four general phases (TEC 2016). These are described in detail in the following subsections.

5.4.2 Consultative processes (1995–2001)

The importance of international technology cooperation was emphasised in the original text of the UNFCCC, which included specific provisions on technology efforts in Articles 4.1 and 4.5,

[53] The effective implementation of the UNFCCC mandate depends on accurately determining the threshold above which anthropogenic climate change becomes dangerous and attributing that change to individual parties (e.g. Smith *et al.* 2009). Defining what constitutes 'dangerous interference' with the climate system is a matter of value judgement influenced by significant scientific uncertainty and socio-economic risk (e.g. Dessai *et al.* 2004). The two-degree target agreed to as part of the Paris Agreement is today an integral part of the international policy discourse, although unitarily framing climate policy through a single benchmark is often criticised as too simplistic, deterministic, and unfeasible (see for instance Hulme 2009, Randalls 2010).

respectively. Therein, parties agreed to 'promote and cooperate in the development, application, and diffusion, including transfer of technologies, practices, and processes that control, reduce, or prevent anthropogenic emissions of greenhouse gases.' Furthermore, 'the developed country Parties…shall take all practicable steps to promote, facilitate, and finance, as appropriate, the transfer of or access to environmentally sound technologies and know-how to other Parties, particularly developing country Parties, to enable them to implement the provisions of the Convention. In this process, the developed country Parties shall support the development and enhancement of endogenous capacities and technologies of developing country Parties' (UNFCCC 1992:7). After the UNFCCC came into force in 1994, member states started a consultative process to develop a shared understanding of the technology needs of developing countries, and the issues surrounding the development and transfer of technology at national, regional, and international levels. In 1997, the COP included provisions on international technology cooperation in Article 11 of the Kyoto Protocol, reiterating the need to 'cooperate in the promotion of effective modalities for the development, application, and diffusion of, and take all practicable steps to promote, facilitate, and finance as appropriate the transfer of or access to environmentally sound technologies, know-how, practices and processes pertinent to climate change, in particular to developing countries' (UNFCCC 1997:12).

5.4.3 Establishment of Technology Transfer Framework (2001–2010)

To enforce the general agreement on international technology cooperation that had emerged over the previous decade, a Technology Transfer Framework was established in 2001 at COP 7 in Morocco as part of the Marrakesh Accords. An Expert Group on Technology Transfer (EGTT) was created under the Subsidiary Body for Scientific and Technological Advice (SBSTA) and tasked with monitoring and evaluating the implementation of the five main components of the Technology Transfer Framework: (1) technology needs assessments, (2) technology information, (3) enabling environments, (4) capacity building, (5) mechanisms for technology transfer. Technology needs assessments are country-driven processes designed to assist developing country parties to identify and prioritise technologies for mitigating and adapting to the impacts of climate change. The technology information component of the Technology Transfer Framework promotes an exchange of views on technology-related issues and defines the means including hardware, software, and networking to facilitate and improve the flow of information between stakeholders to enhance technology transfer. The technology information component is mainly achieved through the technology information clearing house (TT:CLEAR), which is an online knowledge platform containing information (databases, reports, and case studies, etc.) related to technology. The enabling environments component focuses on enhancing government actions, including macroeconomic reforms, removal of key barriers (regulatory, political, technical, etc.), and strengthening of economic policy and regulatory frameworks to provide suitable market conditions for technology transfer. The capacity building component is considered a crosscutting theme and seeks to develop and enhance existing scientific and technical skills, capabilities, and institutions in developing countries. The final component on mechanisms for technology transfer provides scientific and technical advice on international technology cooperation and specific ways to promote the development and transfer of technologies in developing countries.

In 2004, during COP 10 in Argentina, the EGTT was asked to consider ways to further strengthen the implementation of the Technology Transfer Framework. This assessment resulted in the addition of four sub-themes to the Technology Transfer Framework in 2007 at COP 13 in Indonesia as part of the Bali Road Map. These were (1) innovative options for financing the development and transfer of technologies, (2) ways and means to enhance cooperation with relevant conventions and intergovernmental processes, (3) promotion of endogenous development of technology through the provision of financial resources and joint research and development, (4) promotion of collaborative technology research and development. Furthermore, the COP requested the Global Environmental Facility (GEF), which at the time served as the only operating entity of the financial mechanism of the UNFCCC, to elaborate a strategic programme to scale up the level of investment for technology development and transfer activities. The following year at COP 14 in Poland, the GEF approved the Poznan Strategic Programme on technology transfer, which had three implementing windows: (1) supporting technology needs assessments in developing countries, (2) supporting pilot projects linked to technology needs assessments, (3) disseminating experience on technology activities. In 2010, the GEF submitted a plan for the long-term implementation of the Poznan Strategic Programme. This plan contained enhanced action on five key elements: (1) support for climate technology centres and a climate technology network, (2) piloting priority technology projects to foster innovation and investments, (3) public-private partnerships for technology transfer, (4) technology needs assessment, (5) GEF as a supporting institution for technology transfer. The Poznan Strategic Programme laid the groundwork for the next phase of negotiations on technology development and transfer.

5.4.4 Launch of Technology Mechanism (2010–2015)

A Technology Mechanism was launched in 2010 at COP 16 in Mexico as part of the Cancun Agreements to scale up efforts and action on technology development and transfer. The Technology Mechanism consists of two complementary bodies: (1) Technology Executive

Committee, (2) Climate Technology Centre and Network. The Technology Executive Committee is the policy component of the Technology Mechanism and provides recommendations to the COP on technology-related issues. Superseding the work of the EGTT, the Technology Executive Committee comprises 20 expert members elected by the COP from both developed and developing countries. The TEC undertakes various activities and engages a wide range of stakeholders through thematic dialogues, task forces, workshops, expert meetings, and side events during the COP. In addition to providing annual recommendations to the COP, it also develops policy briefs and other technical documents to enhance information sharing on technology development and transfer. Of particular interest to this chapter, the TEC recently started to embrace the framework for national innovation systems, producing a policy brief with key messages for the COP. This concluded that 'given the time that may be required to broadly strengthen NSIs [national innovation systems], it may be useful to focus on national and international actions that can help to accelerate prioritized climate technology innovation … *greater efforts to build the science, technology and innovation capabilities of developing countries are critical for accelerating their climate actions'* [emphasis added] (TEC 2015:11). The Climate Technology Centre and Network is the operational arm of the Technology Mechanism and comprises a global network of public and private organisations. The Climate Technology Centre and Network is one of the case studies in this chapter and is introduced in subsection 5.6.1.

5.4.5 Introduction of Technology Framework (2015)

In December 2015, the Paris Agreement was adopted at COP 21 in France. The provisions related to the development and transfer of technology are stipulated in Article 10 of the Paris Agreement: 'Parties share a long-term vision on the importance of fully realizing technology development and transfer in order to improve resilience to climate change and to reduce greenhouse gas emissions' (UNFCCC 2015:27). Moreover, Article 10 of the Paris Agreement established a new Technology Framework, replacing the Technology Transfer Framework established in 2001, which is 'to provide overarching guidance to the work of the Technology Mechanism in promoting and facilitating enhanced action on technology development and transfer' (ibid). In the context of this chapter, the key provision of the Paris Agreement is Article 10.5, which states: '*accelerating, encouraging and enabling innovation is critical for an effective, long-term global response to climate change and promoting economic growth and sustainable development'* [emphasis added] (ibid). This suggests that the accumulation of capabilities needed to manage innovation and technological change is deemed an essential prerequisite to address climate change. A timeline of the four general phases of UNFCCC negotiations related to international technology cooperation is presented in Figure 8.

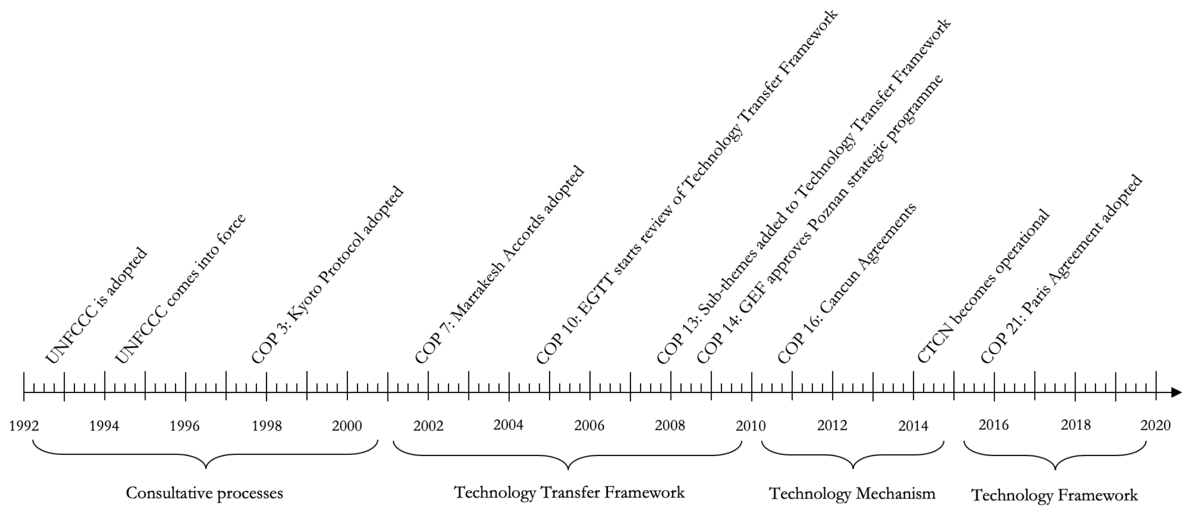

Figure 8 UNFCCC negotiations and decisions related to the development and transfer of technology

5.4.6 A narrow and broad view on technology transfer

Agreement on how best to achieve technology transfer in developing countries is no more settled in academia than in the world of politics (Coninck and Sagar 2015). Drawing on the academic literature, it is possible to discern a narrow and broad view of the technology transfer process (Ockwell and Mallett 2012). The former mainly builds on transaction costs theory and the product-lifecycle, where technology can be understood to diffuse from a single location. The narrow view of technology transfer is primarily associated with the movement of capital goods, which can be transferred between countries using relatively simple market mechanisms. Innovation and technological change are understood to take place primarily in developed countries, whereas developing countries serve as passive recipients involved in the utilisation and replication of technology. This suggests a relatively simple process of accumulating the resources and expenditures needed to acquire externally supplied technology. The narrow view of technology transfer is discernible in numerous climate change reports (see for instance World Bank 2010). This notion of technology transfer as a seamless one-way flow of knowledge, resulting in the automatic delivery of local knowledge spillovers is inappropriate and based on inconclusive evidence (Crespo and Fontoura 2007). Specifically, the narrow view ignores the established insight that technology transferred always has to be optimised and adapted to local conditions (Bell 2012).

In parallel to the narrow view, a broader and more complex view on technology transfer has developed since the 1980s, which emphasises the techniques, processes, and skills needed to not only operate and maintain but also manage and change technology in order to effectively optimise and adapt it to local conditions. The broader view generally considers the presence of innovation capabilities as an essential precondition for achieving technology transfer; that is, the process is inherently contingent on actors and organisations having the appropriate knowledge base and necessary absorptive capacity to effectively appropriate and apply externally acquired knowledge. This is termed the broad view because the formation of innovation capabilities in developing countries involves a comprehensive and more complex set of organisational arrangements (Lema and Lema 2012). The broad view has gained increasing importance. For instance, it is evident in the widely used IPCC definition, which describes technology transfer as: 'a broad set of processes covering the flows of know-how, experience and equipment for mitigating and adapting to climate change amongst different stakeholders such as governments, private sector entities, financial institutions NGOs and research/education institutions ... the broad and inclusive term 'transfer' encompasses diffusion of technologies and technology cooperation across and within countries. ... *it comprises the process of learning to understand, utilise and adapt it to local conditions and integrate with indigenous technologies'* [emphasis added] (2000:3). Based on the broader view, technology may be transferred through different mechanisms, including the movement of goods through trade, technology licensing, joint ventures and acquisitions, global value chains, research and development collaborations, foreign direct investment, movement of people through migration. Studying the different phases of technological catch up in China and India, Lema and Lema (2012) elaborate and place these on a continuum between conventional and unconventional mechanisms according to their level of complexity between cross border interaction and internal efforts and investment required by the technology supplier and importer. In general, technology transfer requires close and extended interaction between the supplier and importer; thus, the link between innovation in one location and its diffusion in another cannot be considered a seamless process.

The different phases of negotiations under the UNFCCC do not reflect a clear-cut distinction between the narrow and broad view, though arguably the understanding of technology transfer as a deliberate and coordinated process that is contingent on the availability of innovation capabilities has been apparent since the establishment of Technology Transfer Framework in 2001. At the same time, however, policy support for innovation capability formation in developing countries has mainly focussed on strengthening public sector organisations. By contrast, the private sector has been underemphasised because the deliberate and targeted support of firms remains controversial and conflicts with intellectual property rights (e.g. Ockwell *et al.* 2010, Rai *et al.* 2014, Abdel-Latif 2015). Nevertheless, the launch of the Technology Mechanism arguably represents a break from more conventional approaches to technology transfer by the UNFCCC in the past to one that emphasises international technology cooperation between public and private sector organisations as the essential means to enhance interactive learning in national innovation systems to complement the formation innovation capabilities in developing countries (TEC 2017).

5.5 Methodology and research design

This chapter aims to develop an understanding of how the formation of global innovation networks may work to connect and enhance processes of interactive learning in national innovation systems and in what way international technology cooperation in the context of climate change complements the creation and accumulation of capabilities needed to manage innovation and technological change. The United Nations Framework Convention on Climate Change established in 1992 is the main policy framework for adapting to and mitigating climate change. A multitude of initiatives for international technology cooperation has since emerged in parallel and in support of the multilateral process. Few attempts have been made to comprehensively map this emerging institutional landscape of international technology cooperation. For instance, this knowledge gap is highlighted in the contribution by Ockwell *et al.*: 'Despite its policy salience, the field is therefore characterised by a distinct lack of empirical or theoretical work dealing with the specific context of climate technologies and in particular collaborations' (2014:402). The empirical part of the chapter seeks to enhance the understanding of the suite of initiatives that exist for international technology cooperation to address climate change. The analysis is divided into two main parts. The first part probes two innovation intermediaries: (1) Climate Technology Centre and Network of the United Nations Framework Convention on Climate Change, (2) International Energy Agency Technology Collaboration Programmes. The second part maps the broader landscape of international technology cooperation in the context of climate change.

5.5.1 Data collection

The empirical part of the chapter draws on the following three sources of data: (1) interviews, (2) participant observation, (3) documentary evidence. To obtain a full description of the innovation intermediaries identified in the mapping, twenty in-depth semi-structured interviews were conducted with representatives of the initiatives. Interviews were conducted in 2017 and 2018 and, where possible, at the headquarters of the respective initiatives in Copenhagen, London, and Paris. An interview guide with open-ended questions and covering relevant themes was prepared and followed during the interviews. Interviewees were asked to describe the main innovation activities of their respective initiative and provide relevant examples of international technology cooperation in the context of climate change. Based on the conceptual framework, interviewees were then asked to reflect upon the modes of learning in global innovation networks. For reliability, verification of the written description of the initiatives was subsequently pursued, thus ensuring the validity and credibility of the findings. Participant observations at the 22nd and 23rd Conference of the Parties of the United Nations Framework Convention on Climate Change in Marrakesh in 2016 and Bonn in 2017 allowed a unique opportunity to monitor the multilateral process related to international technology cooperation. The active participation approach facilitated informal discussions with policymakers during side events and exhibits. This allowed for a comprehensive understanding of international technology cooperation, which would have been unobtainable from passive observation and other methods of data collection.[54] Documentary evidence included official policy documents, white papers, reports, presentations, and newsletters.

5.5.2 Case selection and mapping

Considering the growing number and variety of international cooperative initiatives that have emerged in parallel to the United Nations Framework Convention on Climate Change since 1992, it initially proved challenging to gain an overview of all initiatives of relevance to this research. Although information is readily available from different sources, there is not one single location for accessing information on international technology cooperation in the context of climate change. Consequently, a set of criteria and a taxonomy was used in the mapping to gain insight and familiarity with the list of identified innovation intermediaries. The criteria used to filter the list of innovation intermediaries identified in the mapping is described in section 5.7. To determine the sample population, the author drew on the two public databases: (1) Climate Initiatives Platform and (2) Non-State Actor Zone for Climate Action.[55] The former contained 228 international cooperative initiatives while the latter listed 77 initiatives. Every effort was made to ensure that the sample was as accurate and complete as possible. However, owing to the data collection method, which mainly relied on desk-based research, omissions and inaccuracies are possible. Consequently, the results of the mapping should not be regarded as an exhaustive description of the total population. A multiple case study approach was then selected as the method for research. This allowed the observation of contemporary phenomena in a way that not only examined the relationship between the conceptual constructs developed in the framework for global innovation network but also how the content of these relationships compared across multiple cases. The two cases are explorative in nature, guided by and limited to the categories developed in the conceptual framework. The case studies have both intrinsic and illustrative value. They have intrinsic value because the Climate Technology Centre and Network is the main innovation intermediary under the United Nations Framework Convention on Climate Change, whereas the International Energy Agency Technology Collaboration Programmes is a key initiative

[54] Furthermore, participation in other events including the 10th and 11th CTCN Advisory Board meetings and various thematic dialogues organised by the TEC enhanced the understanding of international technology cooperation under the UNFCCC.

[55] The Climate Initiatives Platform is managed by the UNEP whereas the Non-State Actor Zone for Climate Action platform is hosted by the UNFCCC and managed by the CDP (formerly the Carbon Disclosure Project). The two populations were crosschecked with previous mappings (see Coninck *et al.* 2008, Sagar 2010, IEA 2014, UNFCCC 2016, Lindner *et al.* 2017).

for international technology cooperation outside of the convention. Both initiatives share the ambition to enhance international technology cooperation through the formation of global innovation network but provide contrasting modes of learning. This gives them illustrative value for the observed conceptual diversity of global innovation networks described in Table 12.

5.5.3 Taxonomy of innovation intermediaries

To gain familiarity with the list of identified innovation intermediaries, a simple taxonomy is proposed. Drawing on IEA (2014) and Ockwell *et al.* (2014) the elements considered in the taxonomy are (1) technology focus, (2) innovation cycle, (3) institutional basis. *Technology focus* is classified in the taxonomy as being either individual or multiple, depending on whether the innovation intermediary focuses on specific priorities and circumstances of an individual technology or across a range of technologies or sectors. Rather than a technology focus on individual technologies, most identified initiatives operate on an opt-in basis, allowing actors and organisations to readily identify and cooperate on technologies consistent with their interests, priorities, and resources. *Innovation cycle* relates to the various stages in the innovation process that the innovation intermediary supports. For pedagogic reasons, the innovation cycle is classified here using a modified version of the linear model on innovation, comprising four general stages: (1) research, (2) development, (3) demonstration, (4) deployment. It is acknowledged that this is a simplification of the systemic nature of innovation. However, in doing so, the mode of learning derived from global innovation networks can more easily be discerned. Research and development refer to work undertaken to develop knowledge and/or devise applications of existing knowledge directed towards the development of new technology. Demonstration refers to the construction of prototypes or pilots for testing and demonstrating the feasibility of technology. Deployment refers to the diffusion of knowledge and experience to promote the uptake of proven technologies. Most innovation intermediaries have a broad scope and target multiple stages of the innovation cycle. *Institutional basis* refers to whether an initiative is founded by way of an international legally binding agreement, which brings with it a formal legal status as an intergovernmental organisation, or as an international forum through a political declaration with non-legally binding terms. Most of the identified initiatives were founded as international forums, and several are hosted by existing intergovernmental organisations. International forums based on lighter institutional structures possess the advantage of being able to form quickly in response to changing priorities, but also more easily face resource constraints. The elements in the taxonomy are not absolute and the classification of initiatives is not clear-cut. In cases where an initiative potentially fitted more than one category, a judgement was made regarding the category that best characterises the initiative.

5.6 Multiple case studies of innovation intermediaries in the context of climate change

The first part of the analysis explores in-depth two innovation intermediaries identified in the mapping: (1) UNFCCC Climate Technology Centre and Network, (2) International Energy Agency Technology Collaboration Programmes. Each case starts with a detailed account of the technology focus, innovation cycle, and institutional basis based on the taxonomy presented in the previous subsection, thereby providing a context for understanding how the innovation intermediary contributes to enhancing processes of interactive learning in national innovation systems through the formation of global innovation networks.

5.6.1 UNFCCC Climate Technology Centre and Network

The Climate Technology Centre and Network (CTCN) was established in December 2010 at COP 16 in Mexico as the operational arm of the UNFCCC Technology Mechanism. The objective of the CTCN is 'to stimulate technology cooperation and enhance the development and transfer of technologies to developing country parties at their request' (UNFCCC 2011). The CTCN consists of two main parts; a *climate technology centre* (CTC) located in Copenhagen, Denmark, and a global *network* of public and private entities, which together deliver its three core services: (1) provision of technical assistance at the request of developing countries, (2) access to information and knowledge on climate technologies, (3) outreach and capacity building activities among climate technology stakeholders. The CTCN is hosted by UNEP in collaboration with the United Nations Industrial Development Organisation. Moreover, the CTCN is supported by 12 *consortium partners* with specialised knowledge and expertise on adaptation to and mitigation of climate change.[56] At the end of 2017, the CTCN comprised 396 public and private entities. For the purposes of this chapter, these are categorised according to the subcategories listed in Table 2. Firms constitute the largest group of network members (43%), followed by other entities (33%), and knowledge institutes (24%). 192 of the network members (48%) are registered in developed countries, while 193 (49%) are based in developing countries. 11 (3%) network members are categorised as intergovernmental organisations or international forums. The case studies in this chapter aim to develop an understanding of how innovation intermediaries contribute to enhancing processes of interactive learning in national innovation systems. Specifically, the focus here is on the first of the core services of the CTCN and how the provision of technical assistance complements the development of innovation capabilities in developing countries.

[56] The 12 consortium partners are the Asian Institute of Technology (Thailand), Bariloche Foundation (Argentina), Council for Scientific and Industrial Research (South Africa), Deutsche Gesellschaft für Internationale Zusammenarbeit (Germany), Energy and Resources Institute (India), Energy Research Centre of the Netherlands (the Netherlands), Environment and Development Action in the Third World (Senegal), National Renewable Energy Laboratory (United States), Tropical Agricultural Research and Higher Education Center (Costa Rica), UNEP DTU Partnership & UNEP-DHI Partnerships (Denmark), and the World Agroforestry Centre (Kenya).

5.6.2 UNFCCC Climate Technology Centre and Network technical assistance

The provision of CTCN technical assistance is a demand-driven process based on national ownership. The process can be divided into four general steps: (1) request generation, (2) request processing, (3) response implementation, (4) response closure. The establishment of a national designated entity (NDE) is a prerequisite for a developing country to submit requests for CTCN technical assistance. NDEs serve as national focal points and manage the submission process of technical assistance requests to the CTC and further coordinates the implementation of the response. Moreover, NDEs play a central role in identifying climate technology priorities and capacity building needs in line with national development plans, engaging relevant ministries and agencies, and building networks of climate technology stakeholders.

The technical assistance process begins with the NDE ensuring that the requests generated are aligned with national development plans and priorities. Through consultative processes, the NDE collects inputs and suggestions from relevant stakeholders to maximise synergies and minimise overlaps with previous or current national assessment processes, such as technology needs assessments and low emission development strategies. The proponent is then invited to prepare a proposal in collaboration with the NDE. The proposal explains the scope of the technical assistance requested, how it will contribute to achieving the country's 'nationally determined contributions' (wherein governments as part of the implementation of the Paris Agreement have communicated their intentions to reduce GHG emissions and adapt to the impacts of climate change), the expected timeframe, and the key stakeholders involved. The CTC checks the completeness of the submission and obtains necessary clarifications. To ensure a high quality of technical assistance and avoid bias in innovation process management, requests for technical assistance are screened and checked against eligibility and prioritisation criteria and balancing principles (CTCN 2013). Following this appraisal, the CTC will conclude that the request for technical assistance is: (1) eligible and prioritised, (2) eligible but not prioritised against the balancing principles or prioritisation criteria, (3) not eligible and does not fulfil the guiding principles. The CTC prepares a response plan, typically in collaboration with a consortium partner, detailing the terms of reference for the request for technical assistance, including a schedule of milestones and deliverables, a monitoring and evaluation plan, and an estimated budget.

Once the response plan has been agreed on and approved by the NDE, the CTC determines the type of response warranted. Technical assistance responses are classified as a 'quick response' or a 'response project'. If the response is estimated to cost up to approximately USD 50,000, it is considered a 'quick response', and the CTC contracts the implementation of technical activities to the consortium partner or network member deemed the most capable. If the response costs more than USD 50,000 and up to USD 250,000, it is considered a 'response project'. Here, the CTC will tender the technical assistance to the network to solicit competitive bids against the indicative budget. Irrespective of the classification and type of response provided, the operationalisation of CTCN technical assistance requests entail the formation of global innovation networks that bring together global consortium partners and/or network members with local actors and organisations in order to enhance processes of interactive learning in national innovation systems. The final step of the process relates to the monitoring and evaluation of the technical assistance. This is an essential element in the overall process and is critical to document to donors that the provision of CTCN technical assistance leads to real measurable impacts.[57]

Figure 9 shows the national coverage of technical requests deemed eligible and prioritised in combination with their regional distribution since the CTCN became operational in early 2014. At the end of 2017, 83 developing countries had submitted 195 requests for technical assistance to the CTCN. Among the 134 requests for technical assistance (from 77 developing countries), deemed eligible and prioritised, the CTC was reviewing and designing response plans for 48 and implementing a further 54. Furthermore, at the end of 2017, the CTCN had implemented 32 technical assistance responses. 17 of these were implemented by consortium partners, while network members implemented 14. Excluded are the 61 requests for technical assistance that were either 'eligible but not prioritised' (34), 'withdrawn by the NDE because of changes in priorities' (22), or 'not eligible' (5).

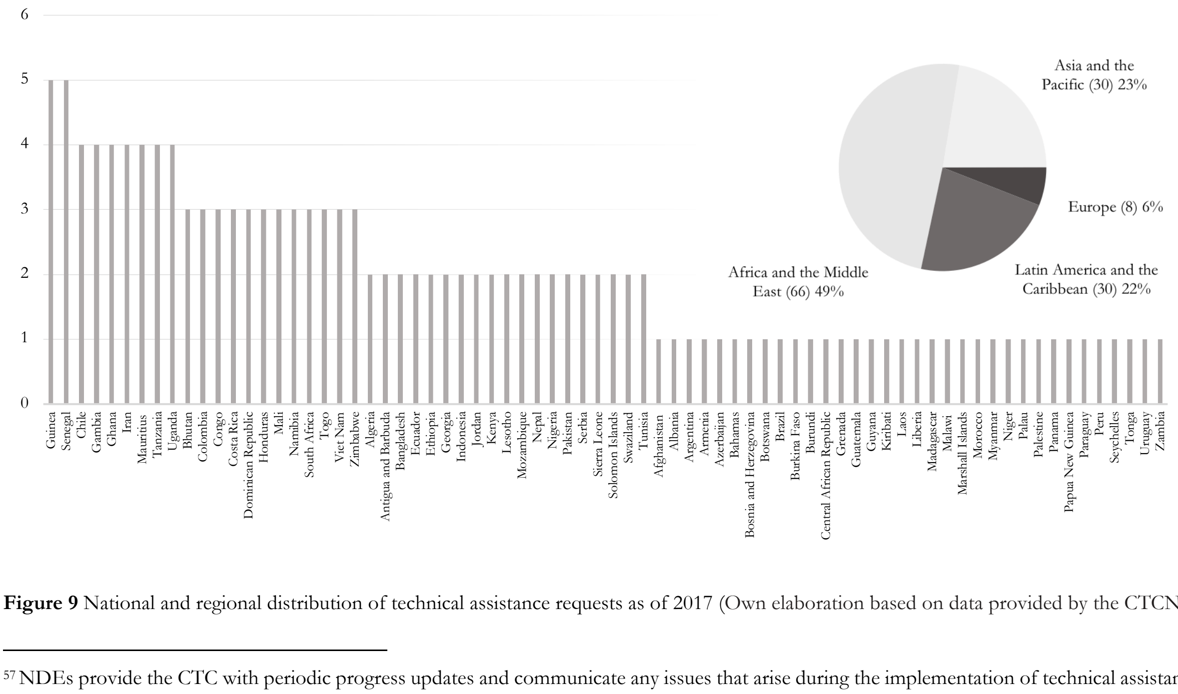

Figure 9 National and regional distribution of technical assistance requests as of 2017 (Own elaboration based on data provided by the CTCN)

[57] NDEs provide the CTC with periodic progress updates and communicate any issues that arise during the implementation of technical assistance. Upon completion of the response, the NDE and lead implementer submit evaluation reports to the CTC, documenting outputs and outcomes achieved as well as expected impacts. Progress on key performance indicators are systematically collected and recorded in a knowledge management system. To demonstrate the value added of technical assistance, the CTC may in some cases decide to develop more elaborate monitoring plans with specific indicators to be monitored over predetermined periods using both quantitative and qualitative methods.

In accordance with its mandate and guiding principles, the CTCN ensured a balanced geographical coverage of technical assistance responses with a preference for requests submitted by the least developed and most vulnerable countries. Figure 10 shows the climate technology focus and the type of technical assistance requested by developing countries.[58] As can be seen, the CTCN mainly supports the later stages of the innovation cycle to enhance the demonstration and deployment of climate technologies. The majority of requests relates to the identification and prioritisation of climate technology options and providing information on the feasibility thereof.

Regarding the institutional basis, the CTCN is accountable to and operates under the guidance of the COP through the Advisory Board, which determines its modalities and procedures based on the functions outlined in the terms of reference (UNFCCC 2011). The Advisory Board is composed of a mix of government representatives from developed and developing countries, representation from academic, business, and NGO community, representatives of the TEC, and other UNFCCC bodies. It meets biannually to discuss and decide on operational matters related to the work programme and budget. It sets up task forces to address issues critical to the operation of the CTCN and advises on the implementation of decisions provided by the COP (UNFCCC 2013). For instance, a key issue since the inception of the CTCN has been how to address its precarious financial situation, which is based on voluntary and often earmarked contributions from donor countries rather than structural funding from the UNFCCC. Other matters relate to strengthening CTCN support in the earlier stages of the innovation cycle and increasing collaboration with other UNFCCC bodies, such as the GEF and the Green Climate Fund.

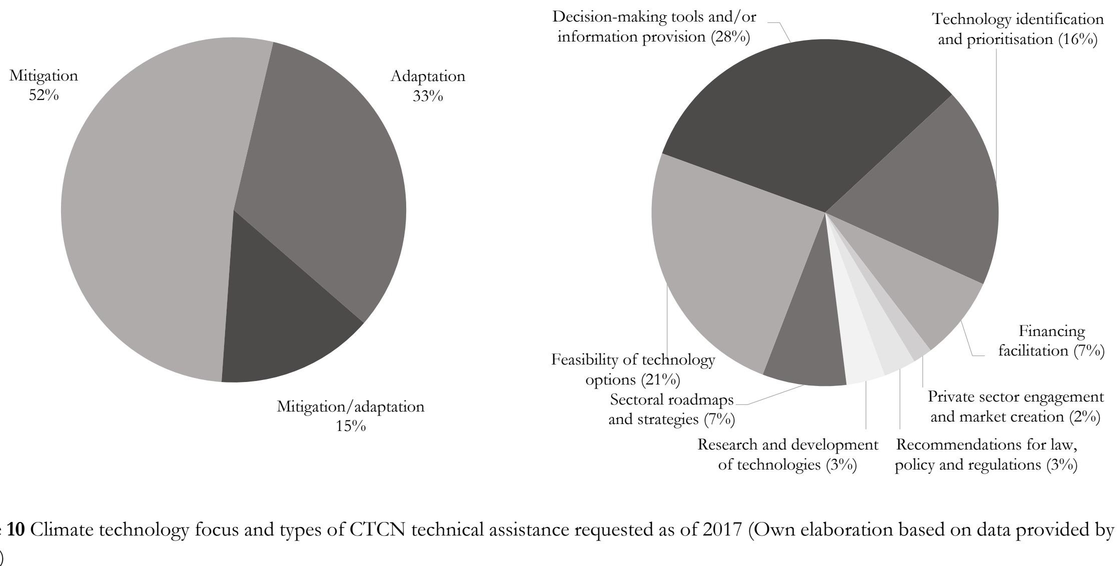

Figure 10 Climate technology focus and types of CTCN technical assistance requested as of 2017 (Own elaboration based on data provided by the CTCN)

[58] Based on IPCC (2000) the CTCN broadly defines climate technologies as any piece of equipment, technique, practical knowledge, or skills for performing a particular activity that can be used to face climate change. As shown in Figure 10, the technology focus of the requests for technical assistance is grouped according to a focus on adaptation (mainly agriculture and forestry, coastal zones, and infrastructure and urban planning) or mitigation (mainly energy efficiency, renewable energy, and waste management) of climate change or a combination of the two.

5.6.3 Knowledge and experience derived from CTCN technical assistance

The CTCN seeks to accelerate the demonstration and deployment of climate technologies through the formation of global innovation networks spanning national innovation systems. The provision of CTCN technical assistance in developing countries relates mainly to identifying and prioritising technology needs and options, creating enabling conditions for proven climate technologies, and facilitating access to climate finance that supports their active demonstration and deployment. In particular, the majority of requests for CTCN technical assistance focuses on enhancing interactive learning via either the production of training materials, the delivery of specific training events, or the design of training programmes. Furthermore, access to information and knowledge on climate technologies is provided through a comprehensive knowledge management system, comprising a technology library, webinars, e-learning courses, and other forms of peer learning and training. Finally, outreach and capacity building activities are organised through international technology events, regional forums, workshops, network meetings, secondments, and an incubator programme. Combined, CTCN technical assistance in and across a range of sectors enables actors and organisations in developing countries to readily identify areas for international technology cooperation that are consistent with their climate technology priorities and needs.

Together this suggests that interactive learning derived from the CTCN is based on the exploitation of knowledge along current and already established technological trajectories. For instance, through targeted CTCN training events and programmes, firms and knowledge institutes gain the knowledge and experience needed to modify and implement techniques and experimental designs and learn how the application of these are affected under different conditions. Experimental development with technology allows practitioners to test how changes to its configuration affect functionality and performance. Through this experience-based learning, based on doing, using and interaction relationships, external knowledge and experience between multiple actors and organisations across national innovation systems are internalised by practitioners and applied to solve practical technical problems in concrete situations. In this way, the provision of CTCN technical assistance contributes to improving engineering and design activities related practical technical problems encountered in the interaction between users and producers in national innovation systems. The national ownership afforded by this demand-driven process allows for a targeted approach to simulate interaction and dynamism between actors and organisations in national innovation systems in developing countries. This is in accordance with its terms of reference, which stipulate that one of the main functions of the CTCN shall be to facilitate '… prompt action on the deployment of existing technology in developing country Parties based on identified needs' (UNFCCC 2010:20).

5.6.4 International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the OECD in the wake of the 1973 oil crisis. The scope outlined in the 'Agreement of the International Energy Programme' was designed to respond to major disruptions in the supply of oil but its mandate has evolved and expanded significantly over the past decades. Today, the IEA examines the full spectrum of energy issues (i.e. energy supply and demand, energy technologies, energy efficiency, energy markets, etc.) and advocates balanced energy policies that incorporate energy security, economic development, and environmental aspects (referred to as the IEA Shared Goals). The IEA comprises 30 member countries; however, given that approximately half the global energy consumption today takes place outside its domain, it engages with a range of partner countries and major emerging economies.[59] The IEA performs various functions, including (1) provision of authoritative analyses and data through flagship publications such as 'World Energy Outlook', 'Market Reports, and 'Energy Technology Perspectives', (2) promotion of energy policies based on diverse and alternate energy sources, (3) provision of expertise and advice on mitigating the impacts of energy production with regard to climate change and air pollution, (4) development of collaborative partnerships with emerging economies to find shared solutions to common energy and environmental challenges. It works with a range of intergovernmental organisations including the International Renewable Energy Agency and the Organization of the Petroleum Exporting Countries and regularly advises in expert discussions at the UNFCCC. Furthermore, it supports a range of international forums, such as the Clean Energy Ministerial, Mission Innovation, and the International Partnership for Energy Efficiency Cooperation.

At the establishment of the IEA, member countries recognised the need to explore alternative sources of energy and energy conservation measures through international technology cooperation. Accordingly, in 1975, the IEA Governing Board, the supreme body of the IEA, established the Technology Collaboration Programmes (TCPs), formerly known as Implementing Agreements, as a flexible mechanism to respond to energy technology challenges through joint research, development, and demonstration activities. The TCPs bring together a wide range public and private sector organisations with a range of expertise in specific energy technologies who wish to address common challenges jointly and share the benefits of their efforts. The aim of this case study is to probe how participation in the TCPs contributes to enhancing interactive learning in national innovation systems in developing countries.

[59] At the end of 2017, the IEA comprised 30 member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Italy, Japan, South Korea, Luxembourg, the Netherlands, New Zealand, Mexico Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. Chile was in the process of accession. Brazil, China, India, Indonesia, Morocco, Singapore, and Thailand had association status with the IEA.

5.6.5 International Energy Agency Technology Collaboration Programmes

A TCP is a contractual relationship established between two or more IEA member countries to jointly carry out a research programme or project. Replacing the 'Guiding Principles' adopted in 1975, the revised 'IEA Framework for International Energy Technology Co-operation' (commonly referred to at IEA Framework) introduced in 2003 simplified the guiding principles of the Technology Collaboration Programmes and provided a legal framework, whereby public and private entities can equitably share the costs and benefits of cooperating on energy technology research, development, demonstration, and deployment (IEA 2003). Each TCP is supervised by an executive committee composed of at least one representative from each participating entity. Participants that represent governments, the European Union (EU), intergovernmental organisations, or entities designated by a government or the EU are known as 'contracting parties'. Since 2003, entities not designated by their respective governments can participate in TCPs as 'sponsors' subject to the prior approval of the IEA Committee on Energy Research and Technology (CERT). Research activities carried out under the auspices of the TCPs include scientist exchanges, information exchange of research results, database management, technology development and pilot plants, technology assessments, feasibility studies, market analysis, modelling and systems analyses, and environmental impact studies, among others (IEA 2016).

Participation in TCPs is based on an equitable sharing of obligations, contributions, rights, and benefits. In general, this implies that participants gain as much as they contribute to the TCP. Treatment of intellectual property rights is usually dealt with in the Implementing Agreement and determined by the individual executive committees on a project by project basis when developing their work programme.[60] In some TCPs, patents resulting from research activities may be filed as appropriate by the inventing participant, whereas executive committees in other TCPs prohibit entities from profiting from such publication. A TCP has a renewable five-year term that is reviewed and approved by request to the CERT. TCPs are funded through either a cost-sharing approach (typically for single joint research activities or experiments), where each participant contributes to a common fund, or a task-sharing scheme, where participants make in-kind contributions. In addition, some TCPs have annual membership fees that finance administrative and secretarial support for the executive committees. Decision-making and priority setting occur at the programme level, where the executive committee approves the annual programme of work, funding structure, and budget. Furthermore, the executive committee establishes the terms of contribution for scientific and technical information and provisions for intellectual property.

[60] The Implementing Agreements were rebranded as 'Technology Collaboration Programmes' in 2015. Today, the term 'Implementing Agreement' is used to refer to the legal text, which governs each of the TCPs. The term 'TCP' was adopted to refer to the activities of the research programmes.

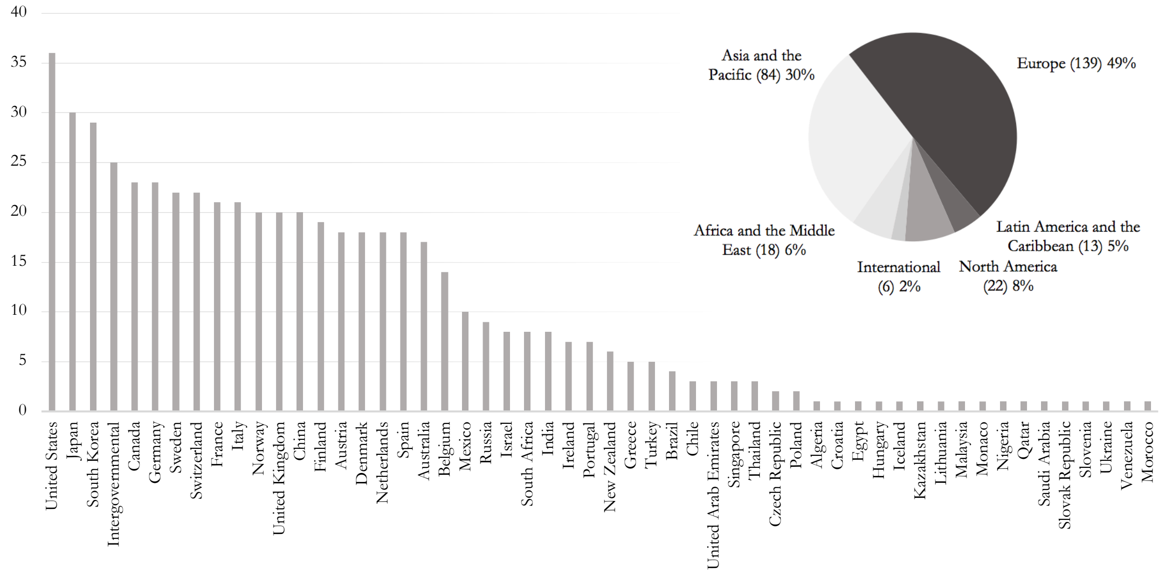

Figure 11 National participation in TCPs and regional distribution of participating entities as of 2017 (Own elaboration based on data provided by the IEA)

At the end of 2017, 38 TCPs were in operation involving almost 300 public and private organisations located in more than 50 countries. From the inception of the TCPs as a member country initiative, the mechanism has evolved to become a global platform for energy technology cooperation. Although entities from IEA member countries represent the majority of participants in the TCPs, the growing interest and involvement of developing countries reflect the global nature of energy and climate challenges.[61] Figure 11 illustrates the national participation in the TCPs in combination with the regional distribution of participating entities. As shown, national participation is led by the United States (with entities participating in 36 TCPs), Japan (30 TCPs), and South Korea (29 TCPs). In total, 77 entities (27%) from 21 developing countries participate in TCPs, whereas 199 (71%) entities participate from 32 developed countries. 6 (2%) entities are categorised as intergovernmental organisations or international forums. For the purposes of this chapter, the public and private entities participating in TCPs have been broken down into the subcategories listed in Table 2. Knowledge institutes constitute the largest group of organisations participating in the TCPs (39%), followed by government bodies (25%), other entities (19%), and firms (17%). Figure 12 below shows the energy technology focus of the 38 TCPs, which cover topics related to (1) energy efficiency, (2) fossil fuels, (3) renewable energy, (4) fusion power, (5) cross-cutting issues. The figure also shows the types of research activities carried out under the TCPs between 1975 and 2015.

[61] This development is also emphasised in the IEA Medium-Term Strategy for Energy Research and Technology 2018 – 2022, which recognises the strategic interest in advancing the global agenda for energy innovation and international technology cooperation through the TCPs.

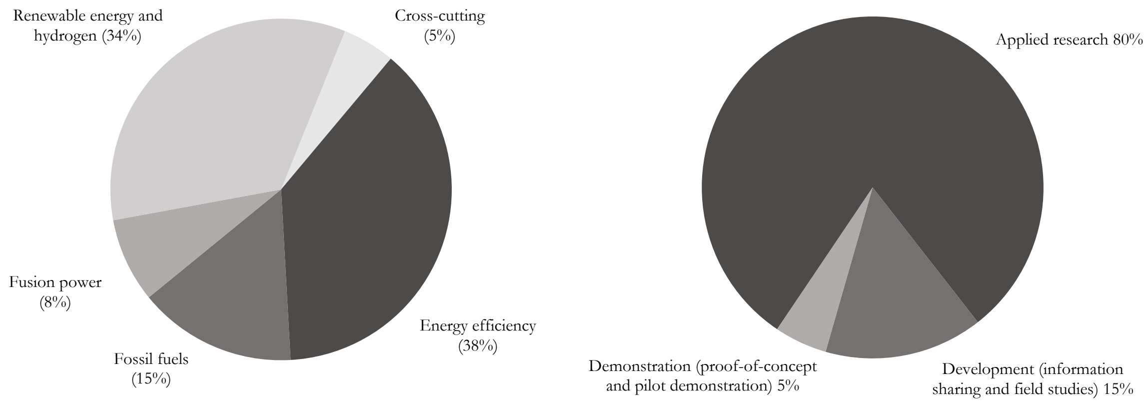

Figure 12 Energy technology focus and activities carried out under the TCPs between 1975 and 2015 (Own elaboration based on IEA 2016)

These can be broadly grouped into three categories: (1) applied research, (2) development, (3) demonstration. As can be seen, the TCPs mainly support the earlier stages of the innovation cycle, where basic and applied research accounts for approximately 80% of research activities and is the focus of the greatest number of TCPs established to date (IEA 2016).

Regarding the institutional basis, the CERT is responsible for implementing IEA activities with regard to energy technology research, development, demonstration, and deployment. The IEA Framework ensures feedback and accountability mechanisms at different levels of the TCPs. The CERT receives annual evaluation and progress reports from the executive committees, which, in turn, receive periodic progress updates of research activities at the programme level. The CERT reports to the IEA Governing Board, which is composed of energy ministers, or their senior representatives, from each IEA member country. The CERT is supported in these efforts by four working parties and two informal expert groups. The working parties consider national policy developments and technology trends, relating to their area of specialisation including end-use technologies, renewable energy technologies, fusion power, and fossil fuels, respectively. The four working parties comprise programme managers and technology experts representing governmental bodies from member countries. They regularly review the achievements of the TCPs and make recommendations to the CERT concerning requests for the extension of these. Furthermore, the working groups advise and support the CERT in carrying out its mandate, facilitate technology cooperation among member countries, and serve as a valuable link to connect TCPs in crosscutting discussions. Together the 38 TCPs, the CERT, the four working parties, and two informal expert groups comprise what is commonly referred to as the IEA Energy Technology Network.

5.6.6 Knowledge and experience derived from the IEA Technology Collaboration Programmes

The rationale for establishing TCPs is to accelerate and achieve cost-effective scientific breakthroughs in energy technologies with a variety of potential applications. The IEA provides a flexible and legal framework for international technology cooperation that effectively ensures the sharing of information, costs, and efforts in order to enhance joint research, development, and demonstration of energy technologies (IEA 2003). Participation in TCPs enables a broader testing base and a variety of application conditions under which experiments can be carried out. Search and experimentation are used to perform approximate tests based on generic properties such as stability, reliability, and transparency to ensure that technological configurations meet specific predetermined engineering designs. Hence, under the auspices of TCP, laboratory and in situ testing, simulations, and comparative life-cycle analyses are carried out (IEA 2016). Furthermore, research activities under TCPs are linked to the working parties and expert groups of the IEA Energy Technology Network, which help to capitalise on a broader knowledge base and a diversity of expertise. This contributes to economic efficiency and an improved rate of technological progress by enabling the sharing of knowledge and experience in a coordinated manner that reduces the cost of research, development, and deployment of energy technologies (OECD 2012).

This science-based learning mode, based on science, technology and innovation relationships, allow practitioners to unravel the complex relationship between structure and function of technology and how potential changes to its configuration affect functionality and performance. Among others, knowledge and experience derived from the TCPs are compiled into data sets that are analysed to form 'benchmarks' and the basis for the harmonisation of standards that underpin regulatory instruments and commercialisation of technologies. Coordinating international research efforts with needs and priorities at the national level typically result in high transaction costs. However, particularly in the early stages of the innovation cycle, where costs and risks are typically high and the prospect for commercial viability not immediately apparent, the TCPs provide for synergies and shared benefits that outweigh the costs of international technology cooperation. Combined, this suggests that interactive learning derived from the TCPs is based on the exploration of knowledge along new technological trajectories. The formation of global innovation networks through the TCPs makes external knowledge linkages more dynamic and better coordinated to respond to new and shifting technological trajectories. The multi-tiered autonomy afforded by this demand-driven structure allows actors and organisations to access certain research topics and specific energy technology advancement in order to jointly respond to common energy and climate challenges, while, at the same time, avoid costly duplication of research efforts in energy technologies.

5.7 Mapping international technology cooperation in the context of climate change

The second part of the analysis maps the broader institutional landscape of international technology cooperation in the context of climate change. The identified innovation intermediaries are qualitatively assessed based on the taxonomy presented in the previous section and schematically grouped according to the modes of learning in global innovation networks. (see Table 12). To explore the framework for global innovation networks and to avoid a purely descriptive account of initiatives for international technology cooperation that would provide little opportunity for comparison, the four criteria below were used to filter the list. In this way, the mapping identifies ten intermediaries including the UNFCCC CTCN and the IEA TCPs.

1. Innovation intermediaries that form global innovation networks – based on the working definition of international technology cooperation in Box 4 – between a minimum of three developed and developing countries.[62]
2. Innovation intermediaries whose primary function is to engage actors in international technology cooperation resulting in the development and/or deployment of technologies.
3. Innovation intermediaries that are government-led and/or government funded.
4. Innovation intermediaries that are well established and for which sufficient information is publicly available in the form of official policy documents and other key texts, such as mission statements, enabling frameworks, decisions texts, white papers, annual reports, and fact sheets.

The first criterion excludes regional initiatives such as the European Climate Knowledge and Innovation Community (Climate-KIC). Bilateral initiatives such as the 2008 EU-India initiative on clean development and climate change or the US-China Clean Energy Research Center (CERC) launched in 2009 are also excluded from the mapping. The second criterion excludes the financial mechanisms under the UNFCCC, including the Green Climate Fund and the Global Environmental Facility, whose primary function is to mobilise climate finance. The regional and multilateral development banks have considerable financial programmes for international technology cooperation; however, these are not included in the mapping. Similarly, financial initiatives such as the Private Financing Advisory Network (PFAN), Renewable Energy and Energy Efficiency Partnership (REEP), or the Climate Investment Funds (CIF) are excluded. The lack of a core technology component excludes capacity building and knowledge sharing initiatives such as the Climate and Development Knowledge Network (CDKN), Renewable Energy Policy

[62] There are no universally agreed criteria for what makes a country developing versus developed and which countries fit these two categories. In this chapter, a country is categorised as 'developed' if listed in Annex I to the UNFCCC and as 'developing' if listed as a non-Annex I country.

Network for the 21st Century (REN21), Global Green Growth Institute (GGGI), and the UN Sustainable Energy for All (SE4ALL). The third criterion limits the mapping to government-affiliated innovation intermediaries, but the framework can be applied to other types of innovation intermediaries, for instance, industry associations such as the Low Carbon Technology Partnerships initiative or city initiatives including Global Covenant of Mayors for Climate and Energy or the C40 Cities Climate Leadership Group. A mapping of these initiatives is worthy in their own right; however, their inclusion was beyond the possibilities and scope of the chapter.

5.7.1 Mission Innovation

Mission Innovation is a global initiative of 22 countries and the European Union launched in November 2015 at COP 21 in Paris to enhance the pace of innovation in clean energy technologies and to support the implementation of the Paris Agreement.[63] The objective of Mission Innovation is 'to accelerate the pace of clean energy innovation to achieve performance breakthroughs and cost reductions to provide widely affordable and reliable clean energy solutions that will revolutionize energy systems throughout the world over the next two decades and beyond' (MI 2016:1). Building on the 'Global Apollo Programme to Combat Climate Change', launched a few months earlier in June 2015, Mission Innovation is an international forum through which governments have voluntarily committed to double their public investment in clean energy research and development between 2016 and 2020.[64] Each member country determines according to its own priorities, policies, and laws the best use of its funding and defines its own path to reach the doubling goal. Altogether, an additional USD 35 billions of public investment in clean energy research and development is committed by its members combined with a pledge of nearly USD 30 billion annually by 2021. Mission Innovation works in tandem with the Clean Energy Ministerial and in cooperation with a range of intergovernmental organisations. Moreover, Mission Innovation has partnered with the Breakthrough Energy Coalition, an independent private sector initiative that consists of a group of high-level investors, who have committed flexible risk capital to support the early stages of the innovation cycle. A Steering Committee comprising member country representatives provides strategic guidance to ensure that Mission Innovation delivers maximum value, while a small secretariat hosted by the United Kingdom Department for Business, Energy, and Industrial Strategy provides administrative support.

[63] As of December 2017, Mission Innovation comprised 22 countries and the European Union: Australia, Brazil, Canada, Chile, China, Denmark, Finland, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, the Netherlands, Norway, Saudi Arabia, Sweden, the United Arab Emirates, the United Kingdom, the United States, and the European Commission on behalf of the European Union (MI 2018).

[64] Spearheaded by Sir David King, the Global Apollo Programme called on national governments to increase public spending on R&D in renewables, energy storage, and transmission technologies to an annual average of 0.02% of GDP between 2016 to 2025 (King *et al.* 2015). In the months leading up to COP 21, much work was done to make the science and research programme a global rather than Western initiative, notably by bringing Brazil, China, and India on board. As part of this development the Global Apollo Programme was renamed Mission Innovation.

Mission Innovation mainly focuses on the exploration of knowledge to deliver scientific and technological breakthroughs along new technological trajectories. The approval of the 'Enabling Framework' at the first ministerial meeting of Mission Innovation in San Francisco in June 2016 set out the general principles and areas in which member countries intend to cooperate on research and development. These include (1) the identification of unaddressed clean energy innovation needs, (2) facilitation of mutually beneficial research and development cooperation and strategic partnerships between governments, the private sector, and other stakeholders, (3) leverage of Mission Innovation as a platform to enhance international research and development cooperation (MI 2016:2). An initial process, where national policy and technical experts exchanged information and views on research and development needs and priorities resulted in the identification of seven innovation challenges suitable for international technology cooperation.[65] Detailed work programmes for each of the innovation challenges are currently being developed to complement existing research efforts at the national level. Engagement in the innovation challenges is voluntary and built around coalitions of interested member countries. The operationalisation of the innovation challenges entails the formation of global innovation networks that bring together interested member countries to exchange knowledge and experience, share information on plans and progress, convene technical workshops, strengthen existing relevant international partnerships, and launch new collaborative activities such as joint funding calls and innovation prizes. As part of these activities, Mission Innovation encourages engagement from firms, knowledge institutes and other entities such as the Breakthrough Energy Coalition.

5.7.2 Clean Energy Ministerial

The Clean Energy Ministerial is an international forum founded in December 2009 by former US Secretary of Energy Steven Chu at COP 15 in Copenhagen to advance clean energy technology development. The objective of the Clean Energy Ministerial is 'to accelerate the global clean energy transition through a voluntary, efficient, global partnership of the world's largest and most forward-leaning economies' (CEM 2016:1). The Clean Energy Ministerial comprises 24 countries and the European Union.[66] It pursues a three-part strategy that includes (1) annual ministerial meetings, (2) public-private engagement, (3) initiatives and campaigns. The annual ministerial meetings serve as a platform for high-level policy dialogue, where energy ministers from member

[65] The innovation challenges are: (1) smart grids and energy storage, (2) off-grid electricity access and small-scale energy systems, (3) carbon capture and storage, (4) second generation biofuels, (5) solar fuels technologies, (6) clean energy materials, (7) heating and cooling systems of buildings.

[66] As of December 2017, the Cleaner Energy Ministerial comprised 24 countries and the European Union: Australia, Brazil, Canada, Chile, China, Denmark, the European Commission, Finland, France, Germany, India, Indonesia, Italy, Japan, South Korea, Mexico, the Netherlands (observer), Norway, Russia, Saudi Arabia, South Africa, Spain, Sweden, the United Arab Emirates, the United Kingdom, the United States and the European Commission on behalf of the European Union (CEM 2017).

countries come together to enhance international technology cooperation on Clean Energy Ministerial initiatives and campaigns to improve clean energy efficiency, enhance clean energy supply, and expand clean energy access. Furthermore, the annual ministerial meetings provide an opportunity to convene public panel sessions and roundtable discussions that bring together energy ministers, firms, knowledge institutes, and other entities for discussions on clean energy deployment. Clean Energy Ministerial initiatives and campaigns take place year-round and focus on providing policymakers and practitioners with the information and tools necessary to improve the policy and business environment to enhance the deployment of clean energy technology. The Clean Energy Ministerial works in close partnership with Mission Innovation and in cooperation with a range of intergovernmental organisations such as the International Renewable Energy Agency and the IEA. A Steering Committee comprising member country representatives supports the so-called Sherpa Group in providing strategic guidance to the Clean Energy Ministerial. A small secretariat consisting of experts on clean energy policy is hosted by the IEA in Paris, France having previously been based at the United States Department of Energy.

The Clean Energy Ministerial mainly focuses on the exploitation of knowledge to accelerate clean energy technology deployment along current technological trajectories. In this way, the complementarity between Mission Innovation and the Clean Energy Ministerial can be clarified: 'While MI [Mission Innovation] focuses on breakthrough R&D for the new technologies of tomorrow, the Clean Energy Ministerial (CEM) focuses on scaling the deployment of technologies and solutions that are available today' (MI 2017). The 'Framework for the Clean Energy Ministerial' adopted at the seventh annual ministerial meeting in San Francisco in June 2016 defines the guiding principles for international technology cooperation. Engagement in the Clean Energy Ministerial initiatives and campaigns is voluntary and based on a distributed leadership approach, where member governments take the initiative to form global innovation networks with partners interested in furthering the demonstration and deployment of particular clean energy technologies. In 2017, member countries cooperated on ten initiatives grouped into four thematic areas including energy demand, energy supply, energy systems and integration as well as crosscutting support.[67] While governments lead Clean Energy Ministerial initiatives and campaigns, participation in the workgroups is open to public and private entities from any country to share best practices and leverage knowledge and experience to realise faster demonstration and deployment of cleaner energy technologies in the member countries.

[67] The Clean Energy Ministerial initiatives and campaigns include: (1) Electric Vehicles Initiative (EVI), (2) Energy Management Working Group (EMWG), (3) Super-Efficient Equipment and Appliance Deployment (SEAD), (4) Multilateral Solar and Wind Working Group, (5) 21st Century Power Partnership (21CPP), (6) Global Lighting and Energy Access Partnership (Global LEAP), (7) International Smart Grid Action Network (ISGAN), (8) Clean Energy Education and Empowerment (C3E), (9) Clean Energy Solutions Center, (10) Sustainable Cities and Eco-Energy Towns Initiative (CEM 2017). Several Clean Energy Ministerial initiatives are formally organised under the IEA TCPs.

5.7.3 International Renewable Energy Agency

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation founded in 2009 to support countries in their transition to a sustainable energy future. The objective of IRENA is 'to promote the widespread and increased adoption and the sustainable use of all forms of renewable energy' (IRENA 2009:4). IRENA is today the only international organisation exclusively dedicated to accelerating the deployment of renewable energy technologies. The initiation of IRENA was based on deliberations at the 2002 World Summit for Sustainable Development in Johannesburg, the annual G8 Gleneagles Dialogues, and biennial International Renewable Energy Conferences (IREC), and was strongly supported by civil society organisations such as Eurosolar, the World Council for Renewable Energy and the World Wind Energy Association. IRENA works in close partnership with the UN and a range of international organisations and forums including Mission Innovation, and the Clean Energy Ministerial. The statute of IRENA was signed by 75 countries at the founding conference in Bonn in January 2009. By 2017, IRENA had 154 member countries, and a further 26 were in the process of accession (notable exceptions include Brazil and Canada). IRENA performs a wide range of functions including (1) providing authoritative information and analyses and data on renewable energy, (2) advising and supporting countries in their national efforts to transition to renewable energy, (3) promoting the economic, social, and environmental benefits of renewable energy, (4) developing collaborative stakeholder partnerships (IRENA 2017).

Two bodies govern IRENA, namely the Assembly and the Council. The Assembly is the supreme organ of IRENA. It convenes annually to discuss and decide upon issues related to the work programme, budget, adoption of reports, applications for membership and potential amendments to IRENA activities, among others. The Assembly works through consensus to develop policy recommendations to encourage reforms in member countries. The responsibilities of the Council include facilitating consultation and cooperation among IRENA members and reviewing the work programme and annual report. A secretariat located in Abu Dhabi, United Arab Emirates provides administrative support to the Assembly and the Council.

IRENA focuses on the exploitation of knowledge to accelerate the demonstration and deployment of renewable energy technologies along current technological trajectories. The IRENA statute adopted in 2009 outlines the key activities related to international technology cooperation. This includes the intent to 'improve pertinent knowledge and technology transfer and promote the development of local capacity and competence in Member States including necessary interconnections … [and] stimulate and encourage research, including on socio-economic issues, and foster research networks, joint research, development and deployment of technologies' (IRENA 2009:6). IRENA has developed a range of initiatives such as the 'Renewable Energy Roadmaps' and 'Renewables Readiness Assessments' that help countries determine their potential to scale up renewable energy and to assess the suitability of conditions for the demonstration and deployment of renewable energy technologies. Furthermore, IRENA has designed a series project development tools and online platforms that connect a wide range of organisations to increase finance flows towards renewable energy projects, enhance the quality of renewable energy project proposals, link stakeholders via hubs and networks, and diffuse knowledge and information on bankable renewable energy projects (IRENA 2017).

5.7.4 International Partnership for Energy Efficiency Cooperation

The International Partnership for Energy Efficiency Cooperation (IPEEC) is an international forum that seeks to enhance the diffusion of best practices in the field of energy efficiency and promote policies that achieve energy efficiency gains across all sectors. In Aomori in June 2008, energy ministers from the Group of 8 (G8) endorsed the Aomori Declaration, acknowledging that 'all countries, both developed and developing, share common interests for improving their energy efficiency performance … [and] developed countries need to play an important role in cooperation with developing countries, accelerating dissemination and transfer of best practices and efficient technologies' (IPEEC 2008:1). One year later in Rome, Italy in May 2009, the G8, Brazil, China, Mexico, and South Korea established the IPEEC. In 2017, IPEEC membership included 17 of the Group of 20 (G20) economies.[68] Supported by various intergovernmental organisations, IPEEC engages with policymakers and practitioners to provide the responsible national ministries, departments, and agencies with the policy tools and best practices needed to implement policies to develop joint energy efficiency demonstration projects and device adequate policies and measures to enhance the deployment of energy efficient technologies. Specific areas for international cooperation were originally specified in the 'Energy Efficiency Action Plan' endorsed by the G20 at the Brisbane Summit in November 2014. Superseding the 'Energy Efficiency Action Plan', the 'Energy Efficiency Leading Programme' was adopted by the G20 at the Hangzhou summit in September 2016, which provided the basis for a more comprehensive, flexible, and adequately resourced long-term framework necessary for international cooperation on energy efficiency. Two committees govern the IPEEC: A Policy Committee and an Executive Committee. The former governs the overall framework and evaluates the work in the 'Energy Efficiency Leading Programme', while the latter develops proposals for task groups, monitors task group

[68] As of December 2017, the IPEEC comprised Argentina, Australia, Brazil, Canada, China, France, Germany, India, Italy, Japan, South Korea, Mexico, Russia, South Africa, the United Kingdom, the United States, and the European Commission on behalf of the European Union.

progress, and approves their work programmes. The 'Energy Efficiency Leading Programme' outlines 11 work streams for international cooperation.[69] IPEEC members set up task groups under the individual work streams to form global innovation networks between governments, firms, knowledge institutes, and other public and private entities. As part of coordinating the work streams, the IPEEC maintains a continuous dialogue with the G20 Secretariat to avoid the duplication of efforts and ensure the effective implementation of policy principles and energy efficiency measures. Engagement in the work streams and task forces is voluntary and enables participants to share knowledge and experience on policy issues related to the demonstration and deployment of energy efficiency measures that best reflect their national priorities and interests. In this way, the IPEEC mainly focuses on the exploitation of knowledge to achieve energy efficiency gains along current technological trajectories.

5.7.5 Carbon Sequestration Leadership Forum

The Carbon Sequestration Leadership Forum (CSLF) is an international forum established in 2003 to encourage international technology cooperation on carbon capture, utilisation, and storage (CCUS). In June 2003, 13 countries and the European Commission signed the CSLF Charter in Washington, D.C., United States. Over the past decade, CCUS technology has gained political recognition and general acceptance, and today the CSLF comprises 25 countries and the European Union.[70] The objective of the CSLF is 'to accelerate the research, development, demonstration, and commercial deployment of improved cost-effective technologies for the separation and capture of carbon dioxide for its transport and long-term safe storage or utilization' (CSLF 2003:1). CSLF membership is open to national governments that are significant producers or users of fossil fuel and have made commitments to invest resources in research, development, and demonstration activities in CCUS. Various international forums support the CSLF including the Clean Energy Ministerial and Mission Innovation. Furthermore, the CSLF engages with a vibrant academic community that plays an essential role in the research and development of CCUS. A Policy Group and Technical Group govern the CSLF. The former oversees the framework of the CSLF charter, while the latter reviews the progress of cooperative projects and offers recommendations to the Policy Group. A small secretariat hosted by the United States Department of Energy in Washington, D.C. coordinates CSLF meetings and acts as a clearinghouse for information.

[69] The work streams covered under the 2014 Energy Efficiency Action Plan included (1) transport, (2) buildings, (3) networked devices, (4) industrial energy management, (5) electricity generation, (6) finance. The adoption of the 2016 Energy Efficiency Leading Programme resulted in the addition of five work streams including (1) super-efficient equipment and appliances deployment (SEAD), (2) best available technologies and practices, (3) district energy systems, (4) energy efficiency knowledge sharing framework, (5) energy end-use-data and energy efficiency metrics.

[70] As of November 2017, CSLF included Australia, Brazil, Canada, China, the Czech Republic, France, Germany, Greece, India, Italy, Japan, South Korea, Mexico, the Netherlands, New Zealand, Norway, Poland, Romania, Russia, Saudi Arabia, Serbia, South Africa, the United Arab Emirates, the United Kingdom, the United States, and the European Commission on behalf of the European Union.

The CSLF focuses on the exploration of knowledge to achieve scientific breakthroughs in CCUS along new technological trajectories. As stated in the Communiqué of the seventh ministerial meeting of the CSLF held in Abu Dhabi in December 2017, a key objective for international technology cooperation is to 'increase global shared learnings on CCUS by disseminating best practices and lessons learned from CCUS projects and strengthen coordination on R&D efforts globally. Shared learnings can greatly enhance future projects, particularly when first-of-a-kind technologies and/or regulatory frameworks are successfully implemented' (CSLF 2017:2). The CSLF Charter adopted in 2003 defined the key areas where CSLF members cooperate on the research, development, and demonstration of CCUS. These include (1) fostering cooperative research, development, and demonstration projects, (2) resolving potential issues with intellectual property rights, (3) establishing and assessing an inventory of potential research and development needs and gaps, (4) developing strategies that address public perception of CCUS while supporting legal, regulatory, financial, and institutional environments conducive to CCUS, (5) promoting R&D and capacity-building projects in developing countries (CSLF 2003). Since 2003, the CSLF has coordinated more than 30 international research, development, and demonstration projects through the formation of global innovation networks comprising a wide range of actors and organisations. Moreover, in support of its mission and in cooperation with the IEA 'Greenhouse Gas R&D' programme and the Global Carbon Capture and Storage Institute, the CSLF has established an academic task force to strengthen knowledge linkages via academic research programmes, research exchanges, and summer schools between the CSLF Technical Group and Policy Groups and world-leading universities such as Imperial College London, Stanford University, and Tsinghua University.

5.7.6 Consultative Group for International Agricultural Research

The Consultative Group for International Agricultural Research (CGIAR) is a global strategic research partnership launched by the World Bank in 1971 to support breakthrough research and development of climate-smart technologies and practices. The objective of CGIAR is to 'advance agri-food science and innovation to enable poor people, especially poor women, to increase agricultural productivity and resilience, share in economic growth, feed themselves and their families better, and conserve natural resources in the face of climate change and other threats' (CGIAR 2016:1). Initially inspired from the huge successes of the International Rice Research Institute and the International Maize and Wheat Improvement Center set up in the 1960s, today much of CGIAR's impact comes from crop genetic improvement and the development of new and better farming techniques. For instance, the application of synthetic biology has resulted in microbial systems with higher plant nutrition and disease resistance, while new breeding techniques combined with environmental management practices have led to breakthroughs in photosynthesis and nutrient management. Besides, over the past four decades, CGIAR has broadened its focus from breeding and genetic improvement of a few staple crops including wheat, rice, and maize to encompass a larger number of food crops as well as livestock and fish.

After extensive reforms in 2008, today the CGIAR comprises a consortium of 15 international agricultural research centres. Combined, these agricultural research centres employ more than 11,000 scientists and other staff who are implementing a large-scale annual research portfolio of close to USD 1 billion in more than 60 countries in close collaboration with hundreds of partners including knowledge institutes, the private sector, and civil society organisations (CGIAR 2017).[71] The CGIAR Independent Science and Partnership Council provides expert advice and scientific guidance on the research programmes and ensures that these are aligned and complementary to increase the impact of funding by reducing duplication of research efforts among the agricultural research centres. Furthermore, the CGIAR Fund aims to harmonise the efforts of donors to contribute to the objectives of the research partnership, while the Global Forum on Agricultural Research (GFAR) organises a biennial Global Conference on Agricultural Research for Development (GCARD), providing a forum for closer engagement of developing countries to help the CGIAR identify demand-driven research and partnership opportunities. A secretariat located in Montpellier, France provides administrative support to the CGIAR consortium.

CGIAR is mainly focussed on the exploration of knowledge to create new germplasm from which to develop new high yielding seed varieties to enhance food and nutrition security in order to reduce poverty and improve natural resources and ecosystem services in developing countries. Among other things, the research and development activities of CGIAR have contributed to such fields as enhancing the nutritional value of staple crops, pest and disease control through breeding resistant varieties, integrated pest management and biological control, improvements in livestock and fish production systems, genetic resources characterisation and conservation, and improved natural resource management. Research and development activities are guided by the CGIAR Strategy and Results Framework 2016–2030, which provides a robust yet flexible structure through which the agricultural research centres can cooperate in a more collective and concerted manner to deliver impactful results. The Strategy and Results Framework provides a strategic direction for the agricultural research centres, thereby ensuring that these focus on delivering measurable results while, at the same time, avoiding costly duplication of research efforts.

[71] CGIAR receives voluntary contributions funds from member country governments including Australia, Canada, Germany, Germany, the Netherlands, Sweden, Switzerland, the United Kingdom and the United States. Furthermore, the consortium receives substantial financial support from philanthropic foundations, such as Bill and Melinda Gates Foundation and the Ford and Rockefeller foundations.

5.7.7 World Bank Climate Business Innovation Network

The World Bank Climate Business Innovation Network (CBIN) is an international forum launched in November 2016 at COP 22 in Marrakech to support entrepreneurs and small and medium-sized enterprises to deploy clean energy technologies and advance climate action in developing countries. The objective of the CBIN is to 'allow climate technology businesses in developing countries to access the expertise and know-how needed to adapt and adopt innovative business models that have been proven in other countries' (World Bank 2016). The CBIN today comprises more than 30 organisations including government agencies, business investors, venture funds, knowledge institutes, and non-governmental organisations, which leverage their range of experience to support clean technology deployment across a range of developing countries (World Bank 2018). The CBIN is an integral part of the World Bank Climate Technology Programme (CTP), a USD 70 million initiative that helps actors and organisations demonstrate and deploy the most innovative clean energy technology solutions to climate change. The CBIN receives voluntary funding from member country governments in developed countries including Australia, Denmark, Italy, the Netherlands, Norway, and the United Kingdom and is managed by the World Bank infoDev (Information for Development) programme, a global technology and entrepreneurship programme, supporting firms in developing countries to deploy and scale climate technologies and business models to address the challenge of climate change.

The CBIN supports eight World Bank Climate Innovation Centres (CICs) established since 2012 in Ethiopia, Ghana, Jamaica, Kenya, Morocco, Nigeria, South Africa, and Vietnam, respectively.[72] The national CICs were set up to encourage climate technology entrepreneurship in developing countries and to assists start-ups and small and medium-sized enterprises with the knowledge and resources needed to deploy and commercialise clean technologies in a variety of sectors including agriculture, wastewater treatment, and off-grid renewable energy. The national CICs are structured as independent, locally-owned, and privately-run organisations and are typically located near national universities and research institutes. According to the World Bank, since their establishment the national CICs have supported more than 300 entrepreneurial ventures and the start-up of climate-smart businesses and raised more than $9 million in private financing. A small infoDev secretariat, hosted by the Trade and Competitiveness Global Practice Department of the World Bank Group in Washington, D.C., United States, provides administrative support to the national CICs and coordinates the global activities of the CBIN.

[72] The concept of national CICs was originally developed by Professor Ambuj Sagar who proposed that 'a Climate Innovation Centre can be viewed as a facilitating, multi-disciplinary organisation located in a developing country which would have under its umbrella a set of projects that advance the innovation process for key mitigation and adaptation technologies for the particular country/region where it is located. By advancing innovation process for key climate technologies these CICs will accelerate the process of technology transition in developing countries, enabling to meet their climate challenges more effectively and efficiently' (2010:1) (see also Sagar *et al.* 2009, Sagar 2011).

The CBIN was launched to support and increase the scale and impact of the national CICs and deliberately aims to address climate change through market-based solutions. Specifically, the CBIN has three core activities, which include to (1) spread models to enable climate innovation, (2) diffuse disruptive green business models, (3) crowd-in global sources of finance for climate technology innovation. Programmes and activities selected through a competitive process receive funding, mentoring, and training that will help entrepreneurs and small and medium-sized enterprises to significantly increase the competitiveness of their industries through the promotion of energy efficiency measures and clean technology development. Hence, on the one hand, the CBIN provides its strategic partners with country-level insights, access to local markets and channels for crowding in public and private financing into climate technology innovation. On the other hand, through CIC incubation and acceleration, entrepreneurs and start-ups benefit from funding opportunities, support from local institutions, and, importantly, access to professional services, finance, and market connections. In this way, the CBIN mainly focuses on the exploitation of knowledge along current technological trajectories to accelerate clean energy technology deployment in developing countries.

5.7.8 International Solar Alliance

The International Solar Alliance (ISA) is a global initiative announced at COP 21 in December 2015 by Indian Prime Minister Narendra Modi, former President of France Francois Hollande, and former Secretary General of the UN Ban Ki-Moon to address the energy access needs of developing counties by harnessing solar energy.[73] Focussing on the immediate development and deployment of solar power technologies, the objective of ISA is to establish a common platform for international cooperation through which member countries, 'will collectively address key common challenges to the scaling up of solar energy in line with their needs' (ISA 2015:1). The alliance has the stated objectives of mobilising USD 1,000 billion into solar power by 2030 to accelerate the development and deployment of more than 1,000 GW of solar generation in ISA member countries. ISA is a treaty-based intergovernmental organisation. Membership to the alliance was initially open to solar resource-rich countries lying either completely or partly between the Tropic of Cancer and the Tropic of Capricorn, but the scope has since been expanded to all members of the UN. Member countries that do not fall within the tropics can join the alliance on equal terms with the exception of voting rights (ibid:1). The Framework Agreement was opened for signatures at COP 22 in 2016 in Marrakech and has since been signed by 122 countries.

[73] Spearheaded by India, at the time of announcing the ISA at COP 21, Prime Minister Narendra Modi pledged an ambitious nationally determined contribution of installing a 100 GW of solar energy capacity by 2022 while reducing the country's emission intensity by 33–35% by 2030.

Each member country designates a national focal point, which together constitute the permanent network of correspondents of the ISA. Engagement in ISA programmes, projects, and activities is voluntary and based on the rationale that a 'larger and better organized demand will lead to lower costs, catalyse innovation and investments. It will enable participating countries to leverage the opportunities of a greater market power and the learning and network of developers, financiers, innovators and existing institutions in all parts of the globe' (ISA 2019). ISA programmes consists of a set of concrete actions, projects and activities to be taken in a coordinated manner by the member countries. Any member country can propose a programme, provided that it is submitted jointly with at least one other member.[74]

The ISA has a two-tier structure. Representing each member country, the Assembly meets annually at the ministerial level to make decisions concerning the implementation of the Framework Agreement and to coordinate actions to be taken to achieve its objective. A secretariat located in Haryana, India, provides administrative support to the Assembly and assist the national focal points in preparing proposals for ISA programmes and activities. The secretariat has also launched a Solar Technology Application Resource Centre to support capacity building efforts. Supported by the Schneider Foundation, Tata Foundation and Phillips Foundation, the long term objective is to set up similar resource centres in each of the presently eligible members to facilitate the building of a pool of prospective entrepreneurs and local technicians in assembling solar home lighting systems, solar pumps, solar mini-grids, etc. Moreover, the secretariat is working to build a sizeable corpus fund to which the government of India has already pledged USD 350 million to help sustain the programmes and activities in the long term.

ISA works across the innovation cycle but mainly focuses on the exploitation of knowledge to accelerate the development and deployment of solar power technologies along current technological trajectories. The aim is for ISA member countries to cooperate in making solar energy affordable for the poor, by way of reducing the cost of capital through new business models and innovative financial mechanisms, aggregating demands, promoting networked research and development and demonstration facilities in solar applications, helping in the creation of resource centres and introducing common standards and appropriate benchmarks to ensure quality of solar power technologies used by member countries. Table 14 below categorises the identified initiatives for international technology cooperation according to the modes of learning in global innovation networks and summarises the results from the mapping based on three elements considered in the taxonomy: (1) technology focus, (2) innovation cycle, (3) institutional basis.

[74] As of March 2019, ISA has established five key programmes including (1) scaling up solar applications for agricultural use, (2) affordable finance, (3) scaling up solar mini-grids, (4) scaling up solar rooftop, (5) scaling up solar e-mobility and storage.

Table 14 Mapping of innovation intermediaries in the context of climate change

Elements of innovation intermediaries	Technology focus: individual or multiple	Innovation cycle: research, development, demonstration, deployment	Institutional basis: int. forum or intergovernmental organisation	Year:
Exploration of knowledge:				
1. Consultative Group for International Agricultural Research	multiple (climate-smart technologies)	research, development, and demonstration	international forum	1971
2. IEA Technology Collaboration Programmes	multiple (energy technologies)	research, development, and demonstration	intergovernmental organisation	1974
3. Carbon Sequestration Leadership Forum	individual (CCUS technologies)	research, development, and demonstration	international forum	2003
4. Mission Innovation	multiple (clean energy technologies)	research, development, and demonstration	international forum	2015
5. International Solar Alliance	Individual (solar power technologies)	development, demonstration and deployment	international forum	2015
Exploitation of knowledge:				
6. Clean Energy Ministerial	multiple (clean energy technologies)	demonstration and deployment	international forum	2009
7. International Renewable Energy Agency	multiple (renewable energy technologies)	demonstration and deployment	intergovernmental organisation	2009
8. International Partnership for Energy Efficiency Cooperation	multiple (energy efficiency technologies)	demonstration and deployment	international forum	2009
9. UNFCCC Climate Technology Centre and Network	multiple (climate technologies)	demonstration and deployment	intergovernmental organisation	2012
10. World Bank Climate Business Innovation Network	multiple (climate technologies)	deployment	international forum	2016

The grouping of innovation intermediaries according the exploration and exploitation of knowledge is based on the categories developed in the conceptual framework of global innovation networks

5.8 International technology cooperation as a vehicle for innovation capability formation in developing countries to address the challenge of climate change

Recognising the importance of providing a comprehensive policy response to address the challenge of climate change, a better understanding of the rationale for international technology cooperation is a significant and important goal, both in academic and policy terms.[75] For instance, as explained by Smith, 'given the pervasiveness of the global challenges, there can be little doubt that the future of innovation policy must largely rest on multilateral collaboration if the global challenges are to be addressed successfully' (2017:61). This chapter develops an understanding of how the formation of global innovation networks may work to connect and enhance processes of interactive learning in national innovation systems and how international technology cooperation complements innovation capability formation in developing countries. The framework developed in section 5.2 differentiates global innovation networks based on modes of learning and organisational form and further proposes a model for how external knowledge and experience derived from international technology cooperation may complement the creation and accumulation of capabilities needed to manage innovation and technological change.

By way of illustrating how international technology cooperation contributes to the development of innovative capabilities, the mapping in the empirical part of this chapter brings to light the complementarity between innovation intermediaries in the context of climate change. While some initiatives such as Mission Innovation and the IEA TCPs mainly focus on the exploration of knowledge along new or shifting technological trajectories, other initiatives including the UNFCCC CTCN and the World Bank CBIN concentrate on the exploitation of knowledge along current technological trajectories. What can be made of this diversity? In one sense, it may be simply seen as a positive pluralistic expression of international technology cooperation in the context of climate change. Nonetheless, the growing number and variety of international cooperative initiatives that have emerged over the past decades do raise questions about the right balance, duplication of efforts, and where to allocate resources. On the one hand, there is a need for initiatives that focus on the exploration of new knowledge to deliver scientific breakthroughs in technologies with a variety of potential applications. Any solution to climate change is likely to involve initiatives for international technology cooperation such as the IEA TCPs that allow actors and organisations to access to individual research topics and specific energy technology advancement in a coordinated manner that reduces the costs of research and

[75] International cooperation is at the heart of the 2030 Agenda for Sustainable Development with SDG 17 'Partnerships for the Goals' calling for enhanced 'North-South, South-South and triangular regional and international cooperation on and access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms [and] development, transfer, dissemination and diffusion of environmentally sound technologies to developing countries on favourable terms, including on concessional and preferential terms, as mutually agreed' (UN 2019).

development of new energy technologies. On the other hand, considering the urgency of action needed to rapidly decarbonise existing energy, infrastructure, and industrial systems (see for instance IPCC 2018, UNEP 2018, IEA 2019), it may be that some developing countries are better served by demand-driven structures such as the UNFCCC CTCN that explicitly targets the later stages of the innovation cycle, so as to complement the development of capabilities needed to accelerate and scale the deployment of proven technologies.[76]

A key point to emerge from the broader view is that irrespective of the different mechanisms, international technology transfer as a vehicle for technological catch-up in developing countries is likely to occur only in so far as sufficient innovation capabilities are locally available. Put differently, technology cooperation cannot work without innovation capabilities being locally available. However, at the same time, international technology cooperation can complement the development of these capabilities. This complementarity involves two interacting dimensions. One dimension centres on international technology cooperation as explicitly organised and managed to ensure that interactive learning processes contribute to the creation of innovative capabilities, while the other focuses on ensuring that cooperation contributes to further developing those capabilities through the subsequent optimisation and adaptation of technology to local conditions. The role of international technology cooperation in innovation capability building is, therefore, largely *complementary* and only partly *substitutable* (Fu *et al.* 2011). As alluded to in subsection 5.4.6, the notion of technology transfer can, therefore, hardly be understood in isolation because the use of external knowledge and experience are complementary aspects that are combined in creation and accumulation of innovative capabilities in developing countries (see also Figure 7).

Innovation capability building specifically targeted at actors and organisations at the forefront of efforts to improve energy access could help significantly accelerate and scale up the deployment of technologies that are particularly suited for application in developing countries. Since this research understands the challenge to address climate change in developing countries as related to the demonstration and deployment of proven technologies more than the R&D of new technologies, the author is largely sympathetic to international cooperation that that support capability formation in the later stages of the innovation cycle. Initiatives that focus on delivering targeted innovation capability building through technical assistance, training programmes, and information sharing activities to support the active demonstration and deployment of technologies should be seen as a welcome addition to the often-dominant framing, which relies heavily on a belief in 'techno-fixes' or 'techno-scientific promises' to address the challenge of climate change.

[76] The IPCC 2018 special report concludes that limiting global warming to 1.5°C requires rapid and far-reaching transitions in land, energy, industry, buildings, transport, and cities. Specifically, global net human-caused GHG emissions would need to fall by about 45 percent from 2010 levels by 2030, reaching 'net zero' around 2050.

6. System innovation of innovation systems: Towards an innovation policy framework for addressing the United Nations Sustainable Development Goals

The frame of reference for innovation has changed over the past decade and with it the requirements for conceptual approaches that underpin innovation policy. Innovation scholars and policymakers are taking an increasing interest in exploring the transformative potential of innovation. This is in response to a range of persistent societal and environmental problems that are deeply rooted in our contemporary modes of production and consumption. On this matter, the systems of innovation approach is regarded as overly descriptive and to lack the normative power expected from a policy framework with the ambition to address contemporary societal challenges. It is increasingly understood that addressing societal challenges of the type of the SDGs requires more than optimising innovation systems to fulfil economic policy objectives but also incorporating directionality and a strategic orientation of innovation systems towards a broader range of societal and environmental objectives. This 'normative' turn towards transformative innovation policy is grounded in an understanding of system innovation of socio-technical systems towards more sustainable modes of production and consumption. This thesis argues that capabilities and networks are central features needed to support significantly different directions of innovation along more sustainable development pathways. The previous chapter developed an understanding of how the formation of global innovation networks works to connect and enhance processes of interactive learning in national innovation systems and how international technology cooperation complements the development of capabilities needed to manage innovation and technological change in developing countries. This, in turn, built on the first empirical chapter, which explored how changes to the relationship between the STI and DUI learning modes influences the creation and accumulation of innovative capabilities.

Innovation scholars have started to probe whether and how the systems of innovation approach can be revised to incorporate goal-oriented transformative change towards desired societal and environmental objectives. However, there is still a poor understanding of the possible refinements to the systems of innovation approach that are needed to design innovation policy for transformative change. The best attempt so far to consider insights from the system innovation perspective is that presented by Weber and Rohracher (2012). Moving beyond traditional market and systemic failure rationales, the authors argue that the systems of innovation approach cannot adequately address contemporary societal challenges without inducing long-term strategic processes of transformative change in socio-technical systems. Therefore, there is a need to complement the systems of innovation approach with four additional 'transformational failures' (see Table 15 below). The comprehensive policy framework of Weber and Rohracher (2012) clarifies the relationship between the system innovation perspective and the systems of innovation approach, and it figures prominently in current debates on transformative innovation policy. Nonetheless, it remains unclear how to operationalise the transformational failures and determine in which part of the innovation system that systemic problems occur and what type of systemic instruments that will best address these. Based on the method developed by Wieczorek and Hekkert (2012), this chapter proposes to revise the policy framework of Weber and Rohracher (2012) and incorporate elements of structural analysis that allow devising transformative innovation policy that draws on a combination of the systems of innovation approach and the system innovation perspective. Based on the central premise that policy support for innovation capability formation and networks are essential prerequisites for implementing the SDGs, this chapter proposes that next to the conventional market and systemic failures that impede the performance of innovation systems, there is a need for the systems of innovation approach to incorporate the third category of transformational failures to guide and consolidate the direction of innovation and processes of transformative change in socio-technical systems.

Hence, this chapter takes steps towards the development of an innovation policy framework, which integrates insights from the system innovation perspective and opens up the systems of innovation approach to incorporate directional innovation and a strategic orientation of national innovation systems. The chapter is guided by the following research question: how does a synthesis between the system perspective and the systems of innovation approach legitimise policy interventions in processes of transformative change to address the SDGs? The remainder of the chapter is organised as follows. Section 1 discusses the literature on systemic instruments to address systemic problems of innovation systems. Section 2 presents the system innovation perspective, while section 3 describes the four transformational failures in innovation systems. Section 4 integrates insights from the system innovation perspective into the systems of innovation approach to induce directional innovation and strategically orient processes of transformative change toward desired societal and environmental objectives. Section 5 outlines the methodology while section 6 presents the empirical setting of the chapter. Section 7 assesses of the compatibility of the integrated policy framework with the United Nations Conference on Trade and Development Science, Technology and Innovation Policy review programme and provides input to the work of the UN Technology Facilitation Mechanism established as part of the 2030 Agenda for Sustainable Development to legitimise policy interventions in processes of transformative change to address the SDGs. Section 8 concludes and discusses implications that help to shape our understanding of transformative innovation policy.

Table 15 Categories of systemic problems in innovation systems

	Type of failure:	Failure mechanism:
Market failures	Information asymmetries	Information asymmetries and perceptions of risk result in suboptimal levels of investment in knowledge development
	Knowledge-spillovers	Certain types of knowledge have public good characteristics, leading to spillovers and underinvestment in knowledge development
	Externalization of costs	Markets left unregulated and free to operate on a laissez-faire basis create little economic incentives to reduce negative externalities
	Exploitation of commons	No compensation is paid or received for negative externalities leading to the classical problem of the 'tragedy of the commons'
Systemic failures	Capabilities failure	Insufficient knowledge, skills, and resources influence the capabilities needed to manage innovation and technological change
	Infrastructural failure	Lack or excess of appropriate infrastructures influence technological trajectories and affect the performance of innovation systems
	Institutional failure	Lack or excess of formal and informal institutions to regulate the interaction between the components of the innovation system
	Interaction failure	Too weak or too strong interactions and network relationships affect the performance of innovation systems
Transformational failures	Directionality failure	Lack of means to collectively prioritise, coordinate, and consolidate the direction of change
	Demand articulation failure	Failure to broaden the demand focus beyond economic objectives to societal and environmental objectives
	Policy coordination failure	Inability to collectively coordinate actions and initiatives across economic, social, and environmental dimensions
	Reflexivity failure	Failure to deliberate over the visions, values, and interests of society to explore alternative pathways of development

Based on, among others, Smith 2000, Smits and Kuhlmann 2004, Woolthuis et al. 2005, and Weber and Rohracher (2012)

6.1 Systemic instruments for systemic problems in innovation systems

The aspiration for directional innovation represents a rather significant break with current rationales for innovation policy and in many cases conflict with the conventional understanding of innovation as being collective, uncertain, and cumulative processes. Before exploring the normative turn towards transformative innovation policy, which implies that the systems of innovation approach must not only contribute to economic policy objectives but also strategically orient processes of transformative change to change toward a broader range of societal objectives, three prior policy frameworks that focus on the need for systemic instruments to address systemic problems of innovation systems are briefly introduced and discussed. Notwithstanding these, the literature on systemic instruments is not unified and coherent. The terminology varies among the key contributions, concepts are not yet fully agreed, and definitions and categorisations of systemic problems are not crystallised and partly overlap. Following Smits and Kuhlmann (2004), systemic instruments are hereafter referred to as policy tools that focus on the level of the innovation system rather than its specific components and play an essential role in the management of innovation processes. Specifically, systemic instruments are designed to address systemic problems – here understood as market failures, systemic failures, and transformational failures – that arise at the innovation system level and which negatively influence the pace and direction of innovation. Systemic instruments can, in this way, be understood as an integrated coherent set of tools designed for innovation systems: 'its purpose is to create opportunities and conditions for system formation by influencing elements and connections within the system that would not otherwise emerge spontaneously' (Wieczorek and Hekkert 2012:86).

6.1.1 System failure framework for innovation policy design

The innovation policy framework developed by Woolthuis *et al.* (2005) figures prominently in current debates on the need for systemic instruments to intervene in innovation systems. The authors provide one of the earliest and most comprehensive categorisations of systemic problems that impede the performance of innovation systems. Woolthuis *et al.* (2005) revise the listings of various 'systemic imperfections', which have previously been identified, and propose four general categories of systemic failures: infrastructural, institutional, interaction, and capabilities failures (building among others on Johnson and Gregersen 1995, Carlsson and Jacobsson 1997, Edquist 1997, Smith 2000). Moving beyond single market failure rationales, Woolthuis *et al.* (2005) consider systemic instruments as the means to address the 'systemic imperfections' that impede the performance of innovation systems. In this way, the authors distinguish between cause and effect in terms of the functioning of the innovation system and provide a way to discern in which part of the innovation system that systemic failures occur. This allows for a more targeted approach, where policy measures can be evaluated and improved by involving relevant actors to solve systemic failures arising at the innovation system level.

6.1.2 System-evolutionary approach for innovation policy

The approach of Smits *et al.* (2010) extends the debate on systemic instruments. The authors call for systemic instruments that supports the systemic functions of innovation systems and propose to distinguish between the innovation system in a steady state or a state of structural change. In a steady state, operational innovation policies focus on the implementation of existing, often linear model-based, policy instruments that keep the innovation system vivid and competitive by removing market and systemic failures. However, to fit changing national and global contexts, there is a need to consider innovation systems subjects in need of dynamic structural change. Smits *et al.* (2010) argue that operational innovation policies are limited in their capacity to influence the structure of the innovation system as these are primarily designed to optimise the innovation 'ecosystem' in a steady state. Consequently, there is a need for a new toolbox and the design of systemic instruments based on strategic innovation policies to structurally change the innovation system. Although Smits *et al.* do not explicitly link their conceptualisation of strategic innovation policies to contemporary societal challenges, it is clear that systemic instruments are needed 'to intervene in an orchestrated way in coherent parts of the system to manage steady state systems and guide the transition of structural changes in the system' (2010:442). Hence, the allure of the system-evolutionary approach rests in its ability to set strategic priorities and design systemic instruments that dynamically engage with the level of the innovation system.

6.1.3 Systemic instruments for systemic innovation problems

The key contribution of Wieczorek and Hekkert (2012) explains the rationale for systemic instruments to address systemic failures arising at the innovation system level. The authors elaborate on the work of Woolthuis *et al.* (2005) and develop a comprehensive policy framework, which clarifies the relationship between systemic failures and blocking mechanisms and propose a novel method to link the structural and functional analyses of innovation systems with systemic failures and systemic instruments. Wieczorek and Hekkert (2012) suggest that the functions of the innovation system cannot be improved without altering its structural dimensions. Therefore, the lack of performance of the functions described by Hekkert *et al.* (2007) and Bergek *et al.* (2008) should be seen as an indicator and rationale for policy intervention in the structural composition of the innovation system. Consequently, by altering the structural dimensions, systemic instruments can create circumstances in which the functions of innovation systems can be improved.[77] To clarify, the difference between the functions of innovation systems and the goal of systemic instruments is that the former is mainly descriptive and provides only a snapshot of the innovation system, whereas the latter is prescriptive and moves beyond a static picture of the current situation to support the design of innovation policy that address systemic failures in a more integrated manner. Table 16 summarises the three prior policy frameworks based on three features: (1) systemic failures, (2) systemic instruments, (3) rationale for innovation policy. Following Daimer *et al.*, although these heuristics holds considerable explanatory potential, there is still a poor understanding of the possible refinements of existing systemic instruments that are needed to address the nature and complexity of contemporary societal challenges: 'so far, there is no attempt to build on the innovation system heuristic in order to modulate innovation journeys towards certain desirable objectives … The question is whether systemic policy instruments, which are designed to address the capability of innovation systems, are also suited to address new requirements of research and innovation activities implied by the normative turn of innovation policy' (2012:222).

Table 16 Three policy frameworks to address systemic problems in innovation systems

	Systemic failures:	Systemic instruments:	Rationale for innovation policy:
Woolthuis et al. (2005)	'Systemic imperfections' (infrastructural, institutional, interaction, and capabilities failures) create bottlenecks that hinder the performance of the innovation system	Individual 'policy measures' addressing particular systemic problems can be evaluated ex-post and improved based on structural analysis of the innovation system	Move beyond single market failure rationales to identify and address systemic failures that create bottlenecks and impede the performance of the innovation system
Smits et al. (2010)	(i) steady state: focus on optimising the innovation 'ecosystem' to enhance its capability to innovate (ii) structural state: focus on structurally changing the system to a changing local and global context	(i) operational policies focus on keeping the innovation 'ecosystem' dynamically vivid and economically competitive (ii) strategic policies focus on systemic instruments that dynamically engage with the structure of the system	(i) implement policy instruments that removes market and systemic failures to optimize to the innovation 'ecosystem' (ii) creative destruction ('neue kombinationen') disrupting existing arrangements as the basis for system transformation
Wieczorek and Hekkert (2012)	Systemic failures create blocking mechanisms that hinder the performance of innovation systems by negatively influencing the pace and scale of innovation.	By integrating structural and functional analyses, systemic instruments can be designed to address systemic failures that arise at the innovation system level	Alter the structural dimensions of the innovation system in order for systemic instruments to create circumstances where the functions of the innovation system can be improved

[77] Hekkert *et al.* (2007) propose the following seven functions of innovation systems: entrepreneurial activities, knowledge development, knowledge diffusion, guidance of the search, market formation, mobilisation of resources, and creation of legitimacy. Bergek *et al.* (2008) list the same seven functions but with slightly different labels.

6.2 System innovation

There is a growing awareness that conventional patterns of innovation are insufficient to address contemporary societal challenges. New modes of innovation breaking with prevalent practices and experiences are needed to address societal challenges, such as climate change and resource scarcity, that are deeply rooted in current patterns production and consumption patterns (Steward 2008). These interconnected societal challenges are systemic in the sense that these are tied in complex ways to the material structures produced by society, which, in turn, are difficult to change due to various vested interests and stabilising lock-in processes. Therefore, the expectation of innovation to cope with the nature and complexity of contemporary societal challenges entails substantial changes in society and in the way societal functions are fulfilled (see for instance Grin *et al.* 2010).

In response to these systemic and persistent societal challenges, a system innovation perspective has developed over the past decades, which draws upon a range of theories that explicitly embraces the intersection of the 'social' and 'technological' (Elzen *et al.* 2004).[78] System innovation generally refers to change in the configuration of socio-technical systems. Geels was perhaps the first to use the term 'system innovation' in the context of socio-technical systems: 'system innovation is defined as large-scale transformations in the way societal functions such as transportation, communication, housing, feeding are fulfilled … a system innovation can be understood as a change from one socio-technical system to another' (2004:19).

As previously described, the study of socio-technical systems is, among other things, rooted in theory of complex adaptive systems, which has gained prominence in analysing adaptive patterns of interaction between different system components. Change in the configuration of socio-technical systems entails more than just technological change but also changes in markets, regulations, user practices, and cultural beliefs. The generally accepted theory is that when system elements are coordinated and aligned through a shared understanding of priorities and actions, socio-technical systems are stable and locked-in to particular trajectories. Hence, coordination and alignment of system elements create stability and minor modification in the configuration of socio-technical systems (Rip and Kemp 1998). These self-reinforcing processes entail incremental change, implying a continuation of prevalent practices; an entrenchment creating a powerful momentum that explains why innovation and technological change progress incrementally following particular trajectories (Garud and Karnøe 2003). However, if system elements become misaligned, socio-technical regimes may destabilise and open up to new configurations developed within niches. Put differently, if linkages between the niche and regime level are forged, a wider

[78] The recent review by Sovacool and Hess (2017) discusses different theoretical approaches that explicitly combine the social and technological and how this field has arisen at the interface between science and technology studies and innovation systems studies. System innovation is grounded in an understanding of socio-technical systems but also draws inspiration from the social constructivist approach to technology.

reconfiguration of the socio-technical system may take place. This inherent complexity indicates the uncertainty of system innovation, but it is these co-evolutionary processes that transitions scholars seek to map and understand, and which policymakers aim to instigate and govern.

As previously described, the study and analysis of socio-technical systems has given rise to the multi-level perspective and associated approaches of strategic niche management and transition management.[79] The multi-level perspective does away with the causality of innovation and technological change, and accentuates co-evolutionary processes in different dimensions and at multiple levels (Geels 2002). As with any theory of complex adaptive systems, the multi-level perspective makes certain simplifying assumptions to understand reality (Smith *et al.* 2010). This provides theoretical coherence, but the multi-level perspective remains abstract, and it is unclear how the different conceptual levels are to be applied empirically (Smith *et al.* 2005).[80] Geels (2011) responds to these and other criticisms and emphasises that the multi-level perspective is a middle-range theory designed to explore particular questions on the dynamics of socio-technical systems, which inevitably involves trade-offs between simplicity and realism.

Notwithstanding the limits of the multi-level perspective, the allure of system innovation perspective is that it presents something that goes beyond focussing on social and technological innovation as two separate categories. Grounded in a social constructivist approach to technology, system innovation is based on the understanding that innovation is driven by co-evolutionary processes between the social *and* technological. Technology shapes its social environment and is, in turn, shaped by it. Neither is the sole determinant of the other; the two codetermine each other. This broader and more systemic view of innovation helps to frame the scope and scale of contemporary societal challenges, whose solutions then require more than achieving specific scientific-technological breakthroughs. The tendency to fall back on mission-oriented technology policies of the past to address contemporary societal challenges is widespread. Nonetheless, Mowery *et al.* (2010) suggest that the technical, economic, and social complexities of the societal challenges faced today are more daunting than the ones posed by earlier mission-oriented projects (see also Foray *et al.* 2012, Leach *et al.* 2012, Stirling 2014). For instance, previous mission-oriented programmes such as the Apollo Programme and the Manhattan Project had well-defined objectives that guided the direction of scientific and technological research. These top-down-driven programmes were often solely government-funded and managed by a relatively small number of stakeholders. Furthermore, these projects did not have to compete with various vested interests, stabilising lock-in processes, stranded assets, and sunk costs.

[79] These concepts and approaches have given rise to the research field that focuses on the dynamics of sustainability transitions and the degree to which it is possible to purposely plan and influence these through the coordination of different levels of governance (Markard *et al.* 2012).
[80] See also Shove and Walker (2007) and Meadowcroft (2009) for critical discussions of the multi-level perspective and transition management.

Societal challenges of the type of the SDGs are multifaceted systemic problems involving a wide array of stakeholders at various institutional levels. Hence, the nature and complexity of the societal challenges currently faced necessitate a different kind of policy than for building an atomic bomb or achieving a manned lunar landing. For instance, the impacts of climate change across different functional domains such as energy, food, and mobility are increasingly coupled with and aggravated by the structural embeddedness of a variety of socio-technical systems that are difficult to transform due to various stabilising lock-in processes leading to path dependence and entrapment. A narrow supply-side focus on innovation without considering necessary behavioural changes in established habits and lifestyles are, therefore, insufficient to deal with contemporary societal challenges. On the contrary, a variety of social *and* technological solutions have to be developed in a diverse array of sectors and diffused in a wide range of functional domains.[81]

System innovation offers a new way to deal with the direction of innovation and technological change. It accentuates the need for new policy approaches that mobilise technology, market mechanisms, and regulations across a range of sectors and industries in order to alter existing system dynamics that are tied in complex ways to the set of interacting elements that form socio-technical systems. The implication of this is that 'system innovation is not just a technological, economic, or managerial process, but also a political and cultural process that will require not just leadership, but also inclusiveness and a shared societal vision to drive it' (OECD 2015:7).[82] This, in turn, gives room to demand-side considerations by directing attention away from a singular focus on supply-side actors of innovation (firms, knowledge institutes, and governments) to interactions in networks comprised of a broader and more diverse set of actors, including users, consumers, and citizens (Steward 2012).

6.2.1 Strategic orientation of innovation systems: the normative turn

It is increasingly acknowledged that the systems of innovation heuristic does not provide for a strategic orientation of innovation systems towards societal and environmental objectives (e.g. Schlaile *et al.* 2017, Schot and Steinmueller 2018). This normative turn in innovation policy can be traced back to Smith and Kuhlmann, where it is proposed that 'innovation processes are in need of [systemic] instruments that support functions operating at system level' (2004:25). The authors discuss the rise of systemic instruments, resulting from the end of the linear model of innovation,

[81] The debate about the limits of mission-oriented technology policies is not new and can be traced back to an old text by Nelson, who asked the provocative question, 'if we can land a man on the moon, why can't we solve the problems of the ghetto?' (1974:376). The answer, he suggested, is in the nature and complexity of the challenges faced (see also Mowery *et al.* 2010, Nelson 2012, Foray *et al.* 2012, Martin 2016).

[82] OECD describes system innovation as change in socio-technical systems 'which entails both a production 'environment' (which generates technical innovations) and a user 'environment' (where consumers use technologies to achieve functionalities and enjoy services). System innovation can therefore be seen as a particular kind of innovation which entails substantial changes in both production and consumption' (2015:16).

and the move towards the formulation of innovation policy based on the systems of innovation approach, which implies increased uncertainty of innovation processes and a corresponding need for policy experimentation, evaluation, and learning. Much of the subsequent literature on systemic instruments has focussed on identifying and categorising systemic failures of innovation systems and how best to address these (see for instance Table 16). Nonetheless, to address the societal challenges facing the world today, innovation scholars are calling that the conceptual core of the systems of innovation approach to be reconsidered. For instance, Cagnin *et al.* argue that 'if grand challenges are to be operationalized as rationales for STI policy interventions, the need to transcend these boundaries should be widely appreciated, as should the dynamics of research and innovation processes and the scope and opportunities for steering the reorientation along more sustainable pathways of development' (2012:141). Nevertheless, such a strategic (re)orientation of innovation systems is only to a limited degree dealt with in the systems of innovation approach. Lindner *et al.* refer to this conceptual deficit as a 'governance gap', arguing that 'while the systems of innovation approach primarily serves to identify relevant system elements and supports the analysis of the interplay of interaction and knowledge exchange, it fails to provide conceptual underpinnings on the requirements for an innovation system to identify, assess and ultimately instigate actions with the aim of guiding innovation towards desired directions' (2016:4).

Against this background, innovation systems scholars have started to draw on the system innovation perspective to probe whether the systems of innovation approach can be revised to incorporate goal-oriented transformative change in socio-technical systems (see for instance Kuhlmann and Rip 2018, Schot and Steinmueller 2018, Diercks *et al.* 2019). These scholars argue that system innovation of socio-technical systems – as described in the previous subsection – is critical to address societal challenges; however, they differ in their opinion about whether the systems of innovation approach can be broadened to incorporate directional innovation and a strategic orientation of innovation systems to address a wider range of societal objectives. On the one hand, some scholars maintain that the systems of innovation approach continues to provide a relevant conceptual frame of reference for the design of innovation policy in the context of societal challenges (Lindner *et al.* 2016, Lundvall 2019). On the other hand, there are those who question if the systems of innovation heuristic is appropriate to guide the direction of innovation and processes of transformative change in socio-technical systems (Schot and Steinmueller 2018). The middle ground – the focus of this chapter – is occupied by innovation scholars who argue that the systems of innovation approach needs to be revised and integrate insights from the system innovation perspective in order to strategically orient processes of transformative change toward a broader range of societal and environmental objectives (Weber and Rohracher 2012).

Drawing on illustrative quotes, Table 17 attempts to capture these different positions, concerning the relevance of the systems of innovation approach in the context of contemporary societal challenges. It is acknowledged that this is a simplification that does not serve justice to inevitable anomalies and deviations between these individual (groups) of scholars. The abundance of research done on the systems of innovation approach in the context of societal challenges, such as poverty, inequality, and climate change, is more complex than these stylized positions, and it is fair to assume that none of the positions put forward here are fully coherent or consistent.

This research suggests that the systems of innovation approach continues to provide a useful heuristic; however, it needs to be refined to incorporate the system perspective in order to legitimise policy interventions in processes of transformative change in socio-technical systems to address contemporary societal challenges. In this regard, a key argument is that the system innovation perspective remains only loosely connected to mainstream innovation policy. For instance, Weber and Rohracher argue that 'many important arguments in support of transition-oriented policies remain unheard due to their incompatibility with the prevailing innovation policy framework. From our point of view, the conceptual foundation and actual implementation of transformation oriented innovation policies could be significantly improved by combining the strengths of structurally oriented innovation systems approaches and the transformation-oriented multi-level perspective. Higher acceptance in policy circles could be gained in particular by better integrating the extensive work on system failures as justification for policy intervention' (2012:12). On this matter, the systems of innovation approach has gained wide traction among policymakers and is arguably the most influential innovation policy framework today (see for instance Mytelka and Smith 2002). The benefit of being more compatible with the existing portfolio of innovation policies is, therefore, that it opens up the opportunity for making system innovation perspective more influential in mainstream innovation policy-making.

Hence, a core proposition of this chapter is that the systems of innovation approach needs conceptual refinement to address a wider range of societal objectives. As previously mentioned, the potential of combining the two research fields was already recognised by Geels (2004), Foxon and Pearson 2008, Markard and Truffer (2008), and Alkemade *et al.* (2011) but until recently the systems innovation perspective and the innovation systems literature have largely developed in parallel with little interaction. The next section proceeds by considering the key contribution of Weber and Rohracher (2012), who were probably the first to integrate insights from the system innovation perspective with the systems of innovation approach in a comprehensive policy framework. The following subsections then proceeds to discuss how to operationalise the transformational failures and integrate these into the systems of innovation approach.

Table 17 Relevance of the systems of innovation approach in the context of societal challenges

	Continued relevance:	Proposed revisions:	Rationale for revisions:
Lindner et al. (2016)	'We claim that the [systems of innovation] heuristic itself continues to provide useful analytical lenses and constitutes a valuable conceptual frame of reference for the design of STI policy' (ibid:3)	'We propose to introduce a set of conceptual elements with the objective of enabling the systems of innovation heuristic to incorporate requirements of directionality and normative orientation' (ibid:3)	'These quality criteria [self reflection, anticipation, bridging, and experimentation capacities] shall help to identify assess and ultimately guide innovation processes towards desired directions' (ibid:3)
Weber and Rohracher (2012)	'We argue that such an integration of novel ideas of transition thinking with the current framework of innovation policies and system failures indeed is possible and would help strengthen the strategic orientation of innovation policies' (ibid:1038)	'It is therefore suggested to consider insights from the system innovation perspective more prominently in a policy framework that is based on the innovation systems approach and the associated notion of market and system failures' (ibid:1037)	'[the integration of] transformational failures provide the necessary underpinning for strategic innovation policies that are geared towards stimulating and enabling transformative change in innovation, production and consumption' (ibid:1046)
Schot and Steinmueller (2018)	'Our core proposition is that the existing R&D and national systems of innovation frames for science, technology and innovation policy are unfit for addressing the environmental and social challenges' (ibid:1561)	'What is needed to address social (inequality, poverty) and environmental problems is a focus on the directionality of socio-technical systems, and a more participatory and inclusive approach' (ibid:1561)	'Our view is that it is time to articulate more forcefully and to experiment in practice with a framing for science, technology and innovation policy that emphasises socio-technical system change' (ibid:1554)

6.3 Transformational failures in innovation systems

Weber and Rohracher (2012) argue that the systems of innovation approach cannot adequately address contemporary societal challenges without inducing long term strategic processes of transformative change in socio-technical systems. The authors suggest that a focus on addressing market and systemic failures is too restrictive and that the systems of innovation approach needs to be broaden and complemented with four additional 'transformational failures' to legitimise policy interventions for transformative change in socio-technical systems.[83] It is the opinion of this author that incorporating transformational failures in the systems of innovation approach is a useful way forward and provides the necessary underpinning for transformative innovation policy that is geared towards stimulating and enabling system innovation of established socio-technical systems. In the following subsections, the four transformational failures proposed by Weber and Rohracher (2012) are described and elaborated: (1) directionality failure, (2) demand articulation failure, (3) policy coordination failure, (4) reflexivity failure.

[83] Discussing the limits of the systems of innovation approach, Weber and Rohracher argue, 'proactively stimulating and thus prioritizing specific innovation activities in order to exploit opportunities that could contribute to moving in the direction of desired long-term transformative change is outside of what would be regarded as acceptable in a conventional market or system failure framework' (2012:1042).

6.3.1 Directionality failure

The systems of innovation approach is mainly directed at optimising innovation systems in order to enhance their capacity to innovate and fulfil economic policy objectives (Smits *et al.* 2010). 'Directionality failure' refers to the lack of means for making strategic choices over alternative pathways of development and to collectively explore (and prioritise) specific innovation activities within 'certain corridors of acceptable development paths, inside of which the bottom-up forces of innovation, production and consumption can operate' (Weber and Rohracher 2012:1043). In other words, directionality failure is about opening up the systems of innovation approach to address societal and environmental objectives. However, goal-oriented transformative change is not an integral part of the systems of innovation approach and making directionality explicit in many cases conflicts with the evolutionary impetus of innovation, which are characterised by multiple determinants, feedback loops, and uncertainty (e.g. Fagerberg *et al.* 2006, Smits *et al.* 2010).

Addressing directionality failure involves careful deliberation over the visions, values, and interests of society and collaboratively exploring a diversity of options, while remaining conscious of the various vested interests and lock-in processes driving established socio-technical systems (Stirling 2015). Multiple development pathways have to be explored, which requires attention to hybrid forms of innovation that enhance linkages between local agendas and global sustainability objectives (Ely *et al.* 2013). Directionality failure is not only about opening up the systems of innovation approach to a greater variety of pathways but also about eventually closing down exploration and focussing on specific development pathways (see for instance Stirling 2008). This inevitably involves difficult ex-ante decisions and continuing trade-offs among the interests and visions of different groups of society (Ely *et al.* 2014). Technology-specific policies may, therefore, also be part of the policy mix needed to concentrate resources and develop the knowledge, skills, and capabilities to support significantly different directions of innovation (Azar and Sandén 2011). Put differently; there is a need to collectively coordinate and reach consensus about the direction of change (Weber and Rohracher 2012). In this regard, establishing a shared future vision and setting collective priorities remain a critical part of the portfolio of systemic instruments that are needed to incorporate directionality and a strategic orientation of innovation systems (Schot and Steinmueller 2018). Foresight exercises, technology assessment, and road maps create shared expectations, enable open coordination, and define joint agendas for action (Ely *et al.* 2014). For instance, as explained by Daimer *et al.*, foresight processes set up strategic conversations, engage a diverse set of actors in joint learning processes, and connects a shared future vision to particular development pathways and specific technology options that may ultimately enhance 'the responsiveness of the innovation system towards future challenges' (2012:228).

6.3.2 Demand articulation failure

It is essential to consider demand-side conditions to diffuse innovation in relevant parts of society, and there is broad agreement that systemic instruments should be used to this end. Nevertheless, as argued by Edler and Boon, there is currently little insight into how to broaden the demand focus beyond economic objectives to integrate societal and environmental objectives and 'policies that are designed to support those missions and challenges often ignore the demand conditions and activities' (2018:1). The main reason is that the systems of innovation approach primarily focuses on the early stages of the innovation cycle and, therefore, ignores the diffusion of innovation in society and how this is taken up in the form of products, processes, or services. This is despite the obvious fact that 'no matter how technologically advanced and superior solutions are being developed, they are of little value if they are not successfully implemented, used and diffused' (Coenen *et al.* 2015:13). Weber and Rohracher (2012) refer to this as 'demand articulation failure', because it reflects a lack of learning about the diffusion, implementation, and use of innovation.

System innovation necessarily involves behavioural changes in established habits and lifestyles and the core socio-technical systems around energy, mobility, and food that sustain them. Hence, a narrow supply-side focus on innovation without considering demand-side conditions in established socio-technical systems is insufficient to address societal challenges (Steward 2012). In this regard, experimentation is often promoted as the means to create spaces to learn about user needs and for different actors to work together on a variety of concrete development pathways (e.g. Torrens and Schot 2018, Turnheim *et al.* 2018). For instance, urban living labs provide spaces to consider demand-side conditions and to learn from the diffusion of innovation into relevant parts of society by involving citizens as testers and users of new products, processes, and services (recycling, car-free zones, local energy cooperatives, for instance) in order to respond to societal challenges in the urban environment. Compared to more professional design and production environments, urban living labs are important means to stimulate and experiment with different kinds of innovation that are highly visible and usable in practice since these are applied in real life settings (Frantzeskaki *et al.* 2017). Other ways to overcome demand articulation failure to incorporate directionality and a strategic orientation of innovation systems relate to public procurement (Edquist and Zabala-Iturriagagoitia 2012, Edler and Yeow 2016). This involves articulation of societal demands, responsible research and innovation, and the careful diffusion, implementation, and use of these innovations in relevant parts of society to meet those societal demands (Owen *et al.* 2012). Hence, by involving a broader and more diverse set of actors, governments and other public authorities may use public procurement and tender processes as systemic instruments to induce transformative change in socio-technical systems.

6.3.3 Policy coordination failure

The nature and complexity of contemporary societal challenges require policy coordination that spans economic, social, and environmental dimensions. In this regard, 'policy coordination failure' refers to a lack of ability to coordinate 'coherent policy impulses from different policy areas in order to make sure that indeed the necessary goal-oriented transformative changes for tackling major societal challenges can be achieved' (Weber and Rohracher 2012:1043). The failure to coordinate concrete actions and initiatives across various context-specific policy domains relates to both horizontal and vertical measures (OECD 2005). Horizontal policy failure refers to the lack of boundary spanning coordination across different sectors (transport, energy, food, for instance) and with cross-cutting policy such as tax policy, fiscal and economic policy, and social policy. Vertical policy failure refers to a lack of coherence across ministries, departments, and agencies at multiple levels of government or ensuring policy coordination between regional, national, and international levels. Addressing policy coordination failures is often suggested to involve a more holistic 'whole-of-government' approach that aims to coordinate, enhance coherence and align policies across economic, societal, and environmental domains. Therefore, innovation policy, as conventionally conceived, is typically implemented top-down with a leading role for government in line with new public management styles of specifying objectives and monitoring performance. However, it is increasingly understood that system innovation of socio-technical systems involves more reflexive, tentative and open-ended processes of working among a broader and more diverse set of actors (Kuhlmann and Rip 2018). This runs counter to the idea of innovation policy to be coordinated by a single actor or to be understood in a linear and rational way. Therefore, top-down policies of picking winners are likely to disappoint, and more open and bottom-up policy approaches, enabling a variety of different development pathways, are advocated (see for instance Schot and Steinmueller 2018). As suggested by Rip *et al.* this calls for new policy approaches that recognise the limitations of incremental and radical innovations towards implementing processes of collaborative experimentation, where 'society becomes a laboratory' (2010:8).[84] In this context of increasing interdependencies and complexities, greater cooperation and coordination among a broader and more diverse set of actors is critical in order to legitimise policy interventions for transformative change in socio-technical systems. This broader and more systemic understanding of innovation is captured in the notion of 'tentative governance' defined by Kuhlmann and Rip as 'provisional, flexible, revisable, dynamic and open approaches that include experimentation, learning, reflexivity, and reversibility' (2018:4).

[84] See also the important discussion by Kuhlmann and Rip (2014) who question if traditional science, technology and innovation policy designs are adequate to cope with the contestation, non-linearity and bifurcations of contemporary societal challenges, which is suggested to require a more dynamic multidisciplinary approach involving multilateral collaboration among a heterogeneous set of actors.

6.3.4 Reflexivity failure

The systems of innovation approach only to a limited degree reflects on the direction of innovation and technological change (Schlaile *et al.* 2017). Weber and Rohracher (2012) refer to the inability of innovation systems to continually monitor progress, to anticipate, and to involve actors in processes of self-governance as 'reflexivity failure'. Processes of governance are therefore identified as part of the problem as these are shaped by and embedded in the same social and institutional structures they seek to transform. In other words, 'established commitments and normative political discourses are already informing the multiple and incommensurable framings being grappled with by the appraisal function of governance' (Smith and Stirling 2007:14). The long-term, adaptive, and goal-oriented character of transformative change of established socio-technical systems implies a need for a continuous monitoring and openness towards alternative pathways, experimentation, and learning. This is what Schot and Steinmueller (2018) refer to as 'deep learning', which is achieved when actors start to question their underlying assumptions. Among other things, 'deep learning' involves breaking the singular confidence in technological fixes, which risks neglecting the dynamic feedbacks and rebound effects that may aggravate existing societal challenges and lead to increased depletion of natural resources, loss of biodiversity, and pollution of the environment (Joly *et al.* 2010).[85] As argued by Diercks *et al.*, 'we thus need to acknowledge that innovations can have negative outcomes and may even exacerbate societal challenges, rather than contribute to tackling them' (2019:883). Similarly, Schlaile *et al.* call for a shift towards innovation systems paradigm dedicated to sustainability transformation arguing that 'sustainability can never be perceived as just a technical optimisation puzzle waiting to be solved. Instead, sustainability itself is a deeply complex normative issue that needs to be made explicit' (2017:3). This implies a need to challenge the often-undisputed pro-innovation discourse of ecological modernisation, which asserts that science, technology and innovation can decouple economic growth from environmental degradation without any fundamental changes in societal structures, lifestyles, or human behaviour. Therefore, addressing reflexivity failures involve a more experimental approach to policy learning, which entails the ability to stop innovation trajectories and associated policy initiatives when these turn out to be less promising than initially expected. This necessarily involves policy experimentation and reflexive governance approaches based on scientific evidence and precautionary principles that take into account the complexity, uncertainty, and ambiguity of innovation (Voß *et al.* 2006).

[85] For instance, as argued by Schot and Steinmueller, 'policy-making technology options are often tested against assumed stable preference such as the need for mobility and provision of long trips by cars as in the electric vehicle example above. Hence the emphasis on batteries and not on new mobility services because the electric vehicles is seen as a substitute for the current gasoline car not as a stepping stone towards a new mobility system. Deep learning assumes that actors critically assess their own preferences and experiment with alternatives' (2018:1563).

6.4 System innovation of innovation systems: a synthesis

Drawing on the system innovation perspective, this section proceeds to discuss how and in what way the four transformational failures may be operationalised and integrated in the systems of innovation approach. Based on the method developed by Wieczorek and Hekkert (2012), it is proposed here to revise the policy framework of Weber and Rohracher (2012) by incorporating elements of structural analysis that allow the development of an innovation policy framework that draws on a combination of the systems of innovation approach and the system innovation perspective. One preliminary point needs to be made here. The method of Wieczorek and Hekkert (2012) was originally designed to combine the structural and functional analysis of technological innovation systems as a mean to 'stimulate sustainability oriented technological innovation' (2012:74). Functional analysis of technological innovation systems is, in principle, a useful heuristic as it focuses on the development and diffusion of new (often sustainable) and radical technological innovations. However, it is argued that, in practice, functional analysis is too technology-focused and in the context of contemporary societal challenges, 'the technological innovation system concept therefore seem less suitable to inform open, challenge-oriented learning processes where a wide range of solutions, including non-technical ones, is taken into consideration' (Daimer *et al.* 2012:231).[86] On the contrary, the nature and complexity of contemporary societal challenges require more than achieving specific scientific technological breakthroughs. The need for fundamental change in the way societal functions are fulfilled calls for a variety of social and technological solutions to be developed in a diverse array of sectors and diffused in a wide range of functional domains.[87] Therefore, it is argued that a narrow supply-side focus on technological innovation without considering necessary behavioural changes in established habits and lifestyles are insufficient to address societal challenges of the type of the SDGs. For this reason, this chapter mainly incorporates elements of structural analysis from the method of Wieczorek and Hekkert (2012) in the policy framework of Weber and Rohracher (2012). Hence, this chapter takes steps towards the development of an innovation policy framework by presenting analytical building blocks that (1) link transformational failures with the structural dimensions of national innovation systems and (2) suggests qualities for the design of new types of systemic instruments that are needed to address the transformational failures that impede directional innovation and the strategic orientation of national innovation systems.

[86] See also Truffer, who argues that in addition to the problematic ex-ante determination of technological solutions 'TIS [technological innovation systems] scholars are blamed to reduce transitions to a simple problem of diffusing new and better technologies, whereas the reorientation of user practices, power relationships, regulatory structures, mind sets and public discourses remains unaddressed' (2015:65).

[87] In this regard, Smith and Saurabh (2015) argue it becomes problematic to compartmentalise social innovation against technological innovation as the potential for transformative change arguably is derived from the hybrid of the two. Hence, delineating one form of innovation (e.g. social innovation, technological innovation, system innovation, open innovation, frugal innovation, pro-poor innovation, grassroots innovation, etc.) against another risk overlooking important interstices.

We start by clarifying the innovation system concept as explained by Carlsson *et al.* (2002) according to whom innovation systems are made up of (1) components, (2) relationships, (3) attributes. *Components* refer to the operating parts of the innovation system, which can be categorised based on the structural dimensions described in section 2.3.3 and listed in Table 2: (1) actors, (2) institutions, (3) networks, (4) infrastructures. *Relationships* refer to the links between the components comprising the innovation system, while *attributes* refer to the properties characterising the components and relationships. Carlsson *et al.* (2002) suggest that innovation systems do not perform optimally, if there are problems related to any of these aspects. This is echoed and elaborated by Wieczorek and Hekkert (2012), who argue that innovation systems do not function when there are systemic problems related to: (1) structural dimensions; for instance, specific components that are central to the performance of the innovation system may be missing (presence issue) or (2) attributes of specific components or their relations in the innovation system; for instance, when an individual component lacks particular capabilities to perform (capability issue) or when relationships between the components of the innovation system are too intense or weak (capacity issue). Following Wieczorek and Hekkert (2012), to express the attributes of specific components or relationships of the innovation systems, terms like capacity, quality, or intensity can be used in both a positive and negative sense. For instance, a network can be too intense or too weak, an institution can be too stringent or too weak etc.

To incorporate the four transformational failures suggested by Weber and Rohracher (2012), it is proposed to identify the type of systemic problem that is causing the transformational failures of national innovation systems by determining: (1) whether a transformational failure is caused by the absence or presence of a specific component of the national innovation system (presence issue) or (2) whether it relates to the attributes of a specific component or relationship of the national innovation system (capability or capacity issue). Following Wieczorek and Hekkert (2012), it is suggested that the identification of transformation failures should be seen as a key indicator and rationale for policy intervention in the structural composition of national innovation systems. Consequently, by altering its structural dimensions, systemic instruments can create circumstances in which the transformational failures of the national innovation system can be addressed. The following subsections seek to clarify the relationship between the transformational failures and the structural dimensions of the national innovation system in more detail.

6.4.1 Actor problems

Transformational failures may be caused by the actors of the national innovation system; a category of systemic problems, which can be disaggregated into two types:

Presence related: Actors that play a central role in the performance of national innovation systems may be absent or simply not acknowledged. It is important to reiterate here that the system innovation perspective is informed by a broader and more systemic view of innovation, which directs attention away from a singular focus on supply-side actors of innovation (firms, knowledge institutes, government, etc.) to interactions in networks comprised of a broader and more diverse set of actors including users, consumers, and citizens (see Table 2).

Capability related: Actors may lack specific capabilities needed to set priorities and collectively prioritise, coordinate, and reach consensus about the direction of change. The inability to establish a shared future vision and to involve relevant actors in system innovation may result from various reasons. For instance, a lack of demand articulating competencies on the part of civil society, or the inability to adequately involve citizens as testers and users of innovation may result in demand articulation failure. It may also be that there is insufficient space to learn about user needs and demands, and to study the diffusion of innovation in society. Furthermore, the lack of horizontal coordination across different policy domains, on the one hand, and vertical coordination between multiple levels (for instance, between regional, national, and international levels), on the other, may lead to policy coordination failure of government and other public sector authorities and result in a lack of regulation and standard setting necessary to guide and consolidate the direction of change. Finally, as explained in the previous empirical chapters of the thesis, there may also be a need for actors and organisations to create and accumulate the capabilities needed to manage innovation and technological change to effectively optimise and adapt technology to changing contexts – the process that is generally referred to as innovation capability building.

6.4.2 Interaction problems

Transformational failures may also relate to the interaction between the components of national innovation systems. This category of systemic problems refers to both interaction between the individual system components and at the innovation system level and may be of two types.

Presence related: Interaction between the individual components comprising the national innovation system may be missing or simply not acknowledged. As argued in previous chapters of the thesis, the framework for national innovation systems generally views interactive learning and innovation as spatially bounded processes. However, this view of interactive learning is challenged as it is increasingly understood that innovation processes may be organised and work between and across interrelated spatial scales. Considering the rapidly the changing geography of innovation, enhancing processes of interactive learning are therefore understood as increasingly enacted through the formation of global innovation networks spanning national innovation systems.

Intensity related: There may be problems with the intensity or quality of the interactions between the individual components of the national innovation system (and across national innovation systems). Strong network problems result in myopia and lock-in when incumbents guided by vested interests fail to open up of the national innovation system to a broader and more diverse set of actors, institutions, and infrastructures. On the other hand, weak network problems result from limited interaction or complementarity between the system components and may impede the exploration and exploitation of knowledge in national innovation systems.

6.4.3 Institutional problems

Transformational failures may also relate to the institutions of national innovation systems. This category of systemic problems refers to both hard and soft institutions and may be of two types:
Presence related: Specific institutions that influence the relationships between the components comprising the national innovation system may be missing or simply not acknowledged.
Capacity related: There may be problems with the capacity or quality of institutions of national innovation systems. Strong institutional voids may have detrimental effects on innovation, interactive learning, and capability building processes that influence the performance of national innovation systems. On the one hand, the absence of hard institutions such as financial, legal, and regulatory systems may hinder innovation by impairing the ability of the public and private sector to operate efficiently. For instance, it is well documented that a lack of enforcement over intellectual property rights (traditionally viewed as a solution to asymmetric knowledge dispersion) may lead to suboptimal levels of investment in knowledge development, which have negative effects on innovation. To succeed in weak institutional environments, there is a need for actors and organisations to develop adaptive business models to circumvent strong institutional voids. On the other hand, too stringent institutions may also stifle the exploration and exploitation of knowledge in national innovation systems by creating environments, which favour incumbents and vested interests, what is often referred to as the appropriability trap (see for instance Woolthuis *et al.* 2005). Moreover, soft institutions such as customs, norms, and established practices influence the relationships between the components of the national innovation systems and may affect the entrepreneurial spirit, tendencies to trust, and risk aversion.

6.4.4 Infrastructural problems

Transformational failures may also relate to infrastructure that supports not only the day-to-day operation of national innovation systems but also their evolution and long-term development. This category of systemic problems may be of two types:

Presence related: Specific types of infrastructure (physical, knowledge, financial) that influence the performance of national innovation systems may be missing or simply not acknowledged.
Quality related: Specific infrastructure in national innovation systems may be inadequate or malfunctioning. For instance, as argued in the previous chapter of the thesis, the advance of information and communication technologies, online platforms, and knowledge management systems have become critical infrastructures that have fundamentally altered the interdependencies of innovation processes. Information and communication technologies not only open up new possibilities for horizontally coordinating the multiple determinants and feedback loops of innovation between and across different sectors but also enable new ways to vertically manage these multi-level processes between interrelated spatial scales through the formation of global innovation networks. Taking advantage of these dynamics requires regulation and investments in knowledge infrastructures to provide affordable and accessible information and communication technology services. Moreover, the development and deployment of environmentally sound technologies require access to finance (including publicly backed guarantees, credit, and liquidity) and new types of risk instruments (blended finance instruments and concessional finance are, for instance, often used to transfer risk from the private to the public sector) that ensure direct and indirect financial support to companies and, in particular, entrepreneurs and small and medium-sized enterprises. To this end, the development of new financial infrastructures, business models, and innovative financial mechanisms becomes as important for system innovation of socio-technical systems as research, development, deployment and diffusion of environmentally sound technologies.

6.4.5 Typology of systemic problems impeding the transformative potential of national innovation systems

To clarify the relationship between transformational failures and the structural dimensions of national innovation systems, a simple typology is proposed below. It is suggested that the four transformational failures suggested by Weber and Rohracher (2012) may be caused by the following categories and type of systemic problems in national innovation systems (see also Table 18 for a schematic presentation of the relationship between transformational failures and the structural dimensions of national innovation systems and suggestions for systemic instruments).

- The presence or capabilities of actors (actor problems)
- The presence or intensity of interactions (network problems)
- The presence or quality of institutions (institutional problems)
- The presence or quality of infrastructures (infrastructural problems)

It follows that structural analysis coupled with that of transformational failures can be used to identify the type of systemic problems that impede the strategic orientation of the national innovation systems. Once established whether a transformational failure is caused by specific actors, institutions, interactions, or infrastructures of the national innovation system, one can ascertain whether the systemic problem occurs because specific components are missing or there are problems with their capability or quality. It is important to clarify here that the difference between the structural dimensions of national innovation systems and the goals of systemic instruments is that structural analysis is descriptive and determines the performance of the national innovation system at a particular moment in time in order to identify the systemic problems that the system faces. On the other hand, the goals of the systemic instruments are prescriptive in the sense that these are meant to support policy designs and the selection of policy instruments that can help address the systemic problems identified in a more integrated and forward-looking manner. Therefore, the relationship between the goals of systemic instruments and the systemic problems causing the transformational failures is considered useful for targeting the structural dimensions of the innovation system in a way that improves its transformative potential.

The typology of systemic problems impeding the transformative potential of national innovation systems does not imply that all actors, institutions, and infrastructures need to be present nor that the interactions between these components need to be optimally balanced for national innovation systems to perform well. Such a suggestion would contradict the evolutionary perspective of national innovation systems described in subsection 2.3.5. Whom to involve and in what capacity they should be involved is context-specific and depends on the type of national innovation system in question. Nonetheless, it is suggested here that an overview of the structural dimensions and their relationship to the type of systemic problems that may cause transformational failures is a useful first step for policymakers who (1) seek understand the dynamics influencing the strategic orientation of the national innovation systems and (2) stimulate the combinations of systemic components that have a greater chance to influence goal-oriented transformative change in socio-technical systems. To summarise, in the revised policy framework of Weber and Rohracher (2012), the transformational failures are analysed through the perspective of the structural dimensions to identify the type systemic problems that impede directional innovation and the strategic orientation of national innovation system. The specific type of systemic problem identified should be a precondition for the selection of systemic instruments. Different categories of systemic problems need to be addressed with different types of systemic instruments, which have to be selected in a way that allows for their effectiveness, mutual reinforcement, and orchestrated action.

Table 18 Typology of transformational failures impeding directionality and the strategic orientation of national innovation systems

Transformational failures:	Structural dimensions:	Type of systemic problems:	Illustrative examples of systemic instrument goals needed to address transformational failures of national innovation systems:
Directionality failure	Actors	Presence?	Stimulate and organise the participation of a more diverse set of actors to collectively prioritise and reach consensus about the direction of change
		Capabilities?	Develop the knowledge, skills, and capabilities needed to support significantly different directions of innovation along alternative development pathways
	Interactions	Presence?	Engage in foresight exercises, technology assessments, and road maps to share expectations and enable open coordination
		Intensity?	Mobilise and support a more diverse set of actors to define joint agendas and guide processes of transformative change
	Institutions	Presence?	Develop the presence of relevant institutions needed to guide, coordinate, and consolidate the direction of change
		Capacity/quality?	Strengthen relevant institutions to prevent (or circumvent) institutional voids that impede the directional innovation
	Infrastructures	Presence?	Create supporting infrastructure that contribute to destabilise the lock-in processes, leading to myopia, path dependence and entrapment
		Capacity/quality?	Ensure quality of supporting infrastructure to avoid favouring incumbents and various vested interests driving established socio-technical systems
Demand articulation failure	Actors	Presence?	Stimulate the participation of a more diverse set of actors to broaden demand focus beyond economic objectives to societal and environmental objectives
		Capabilities?	Build demand articulation competencies that consider demand side conditions to learn about the diffusion, implementation, and use of innovation in society
	Interactions	Presence?	Stimulate, mobilise, and support experimentation to create spaces to learn from the active diffusion of innovation into society
		Intensity?	Strengthen interactions by creating designated experimental spaces to work together on a variety of alternative development pathways
	Institutions	Presence?	Develop the presence of relevant institutions that allow for emerging socio-technical configurations to stabilise and diffuse into relevant parts of society
		Capacity/quality?	Strengthen relevant institutions needed for (responsible) innovation to respond to societal demands, for instance through public procurement and tenders
	Infrastructures	Presence?	Create specific types of supporting infrastructure that involve a broader and more diverse set of actors as testers and users of innovation
		Capacity/quality?	Ensure supporting infrastructure that allows for new socio-technical configurations to stabilise through shared expectations, learning, and network building
Policy coordination failure	Actors	Presence?	Stimulate and coordinate the participation of a more diverse set of actors in bottom-up policy learning approaches
		Capabilities?	Build organisational capabilities that allow for the coordination of actions and initiatives that spans economic, social, and environmental dimensions
	Interactions	Presence?	Coordinate actions and initiatives horizontally and vertically across various context specific-policy domains
		Intensity?	Strengthen greater cooperation, coordination and policy learning among a broader and more diverse set actors
	Institutions	Presence?	Develop the presence of relevant institutions that support tentative governance approaches and collaboration among a more heterogeneous set of actors
		Capacity/quality?	Strengthen institutions that allow for increasing interdependencies and complexities ensuring coordination across context-specific policy domains
	Infrastructures	Presence?	Create specific types of infrastructure that allow for horizontally and vertically coordination of innovation processes across different contexts
		Capacity/quality?	Ensure adequate quality of supporting infrastructure that allow for tentative governance approaches and policy learning
Reflexivity failure	Actors	Presence?	Stimulate and organise the participation of a more diverse set of actors to collaboratively explore a diversity of alternative development pathways
		Capabilities?	Strengthen reflexive capabilities of actors to deliberate over the visions, values, and interests of society to connect to a shared future vision
	Interactions	Presence?	Stimulate 'deep learning' where actors start to question and critically assess their own preferences and underlying assumptions
		Intensity?	Question the viability of dominant practices and deliberate over alternative visions, values, and interests of society
	Institutions	Presence?	Develop the presence of relevant institutions that operate on the basis on scientific evidence and precautionary principles
		Capacity/quality?	Strengthen relevant institutions that allows for actors to stop detrimental and environmentally harmful technological trajectories
	Infrastructures	Presence?	Create supporting infrastructure and indicators that enable innovation systems to monitor, anticipate and involve relevant actors in reflexivity processes
		Capacity/quality?	Ensure adequate quality of infrastructure that ensures openness towards alternative development pathways, experimentation, and policy learning

Based on Weber and Rohracher (2012) and Wieczorek and Hekkert (2012)

6.5 Methodology and research design

6.5.1 Case selection

The aim of this chapter is to explore how a synthesis between the system perspective and the systems of innovation approach may incorporate directional innovation and a strategic orientation of national innovation systems to not only contribute to economic growth and competitiveness but also address a wider range of societal and environmental objectives. The empirical part of this chapter provides an assessment of the compatibility of the integrated innovation policy framework developed in the first half of the chapter with the United Nations Conference on Trade and Development Science, Technology and Innovation Policy review programme. Moreover, it aims to provide inputs to the work of the UN Technology Facilitation Mechanism established as part of the 2030 Agenda for Sustainable Development. These UN initiatives are selected as cases for the chapter both because of their intrinsic and illustrative value. They have intrinsic value because: (1) Science, Technology and Innovation Policy review programme is at the core of technical cooperation work in developing countries and it is one of the most apparent innovation capability-oriented policy initiatives of the UN (2) UN Technology Facilitation Mechanism is a key component of the 2030 Agenda for Sustainable Development to mobilise science, technology and innovation for the SDGs. The objective of the second half of the chapter is to interpret the two initiatives with regards to the integrated policy framework. It does not seek to assess the success or effectiveness of the initiatives, but rather to investigate them in light of the recently adopted 2030 Agenda for Sustainable Development. This is in response to recent recommendations of the UN Commission on Science and Technology for Development, on behalf of the UN Economic and Social Council (ECOSOC), to the United Nations Conference on Trade and Development: 'to broaden the framework for national science, technology and innovation policy reviews in order to integrate the Sustainable Development Goals … *with special attention being placed on new trends in innovation that can offer novel possibilities for developing countries'* [emphasis added](ECOSOC 2018:6).

6.5.2 Data collection

The empirical part of the chapter draws on the following three sources of data: (1) documentary evidence, (2) participant observations, (3) interviews. Data collection mainly consisted of official policy documents such as reports, resolutions, and decisions made by UN bodies relevant to the two policy initiatives since the adoption of the 2030 Agenda for Sustainable Development in 2015. The identification of such policy documents was primarily based on searching the Official Document System (ODS) of the UN. Moreover, secondary literature was used to obtain a fuller description of the two innovation policy initiatives and their origins. Every effort was made to ensure that the collection of policy documents was as accurate and complete as possible. However, owing to the data collection method, which mainly relied on desk-based research, omissions, and inaccuracies are possible.[88] Participant observations at the 'Second Annual Multi-stakeholder Forum on Science, Technology and Innovation for the Sustainable Development Goals' held at the UN Headquarters in New York City in May 2017 allowed a unique opportunity to observe the UN Technology Facilitation Mechanism in session, monitor the negotiations related to science, technology and innovation for sustainable development, and to take in the diverse set of opinions articulated through both formal and informal statements. Furthermore, the active participation approach facilitated informal discussions with policymakers during side events and exhibits. This allowed for a comprehensive understanding of the working of the UN Technology Facilitation Mechanism, which would have been unobtainable from passive observation and other methods of data collection.[89] Finally, the author engaged in dialogue with representatives of each policy initiative, providing an additional opportunity for crosschecking and triangulating the policy document analysis to ensure the validity and credibility of the findings.

6.6 Empirical setting: United Nations 2030 Agenda for Sustainable Development

This section presents the empirical setting of the chapter and describes the period of international cooperation in the context of sustainable development leading to the adoption of the SDGs in 2015. Over the past three decades, the international community has increasingly focused on the negotiation of legal frameworks and detailed action plans as the best way to advance intergovernmental cooperation on sustainable development. At the centre of these efforts was the core principles of universal participation and common but differentiated responsibilities. Strongly influenced by 'Our Common Future', which five years earlier had firmly placed environmental issues on the political agenda, world leaders convened in Rio de Janeiro in 1992 at the major UN Conference on Environment and Development. The 'Earth Summit', as it became known, resulted in a global plan of action for sustainable development referred to as the 'Agenda 21'. Centred on multilateralism and the interdependence of nations in the search for a sustainable development path, the Earth Summit marked a new course in the global effort to address sustainable development with the 'Agenda 21' calling for 'the further development of international law on sustainable development, giving special attention to the delicate balance between environmental and developmental concerns' (UN 1992:281).

[88] The ODS of the UN is an online public database launched in 1993, which holds digital UN documents published from 1993 onward and scanned documents published between 1946 and 1993, including all resolutions and decision texts of the six principal organs.
[89] Participation in other events including the 2015 OECD Green Growth and Sustainable Development Forum entitled 'Enabling the next industrial Revolution: Systems innovation for green growth' enhanced the understanding of innovation policy in the context of sustainable development.

From the outset, the UN Commission on Sustainable Development, established by UN General Assembly to ensure effective follow-up of the Earth Summit, was highly participatory and inclusive in its structure and outlook, and engaged in formal proceedings with a wide range of stakeholders. In September 2000, building on a decade of major conferences and summits, world leaders convened at the UN headquarters in New York City. Under the leadership of UN Secretary-General Kofi Annan, member states adopted the Millennium Development Declaration and agreed on a set of time-bound and measurable goals (referred to as the Millennium Development Goals) to be achieved by 2015, including combating poverty, hunger, disease, illiteracy, environmental degradation, and discrimination against women (UN 2000).

In 2012, twenty years after the Earth Summit, heads of states reconvened in Rio de Janeiro for the UN Conference on Sustainable Development (Rio+20) to negotiate the post-2015 sustainable development agenda. Negotiators sought to introduce a new intergovernmental decision-making process to sustainable development, one that shifted away from outdated development assumptions of the past towards a set of common sustainable development goals that were to be global in nature and universally applicable.[90] As reflected in the outcome document 'The Future We Want', at the core of this paradigm shift was the acknowledgement that every country, taking into account common but differentiated responsibilities and respective capabilities, needed to take actions towards a sustainable development path (UN 2012).

The establishment of the UN High-level Political Forum on Sustainable Development, replacing the UN Commission on Sustainable Development was another key outcome of Rio+20.

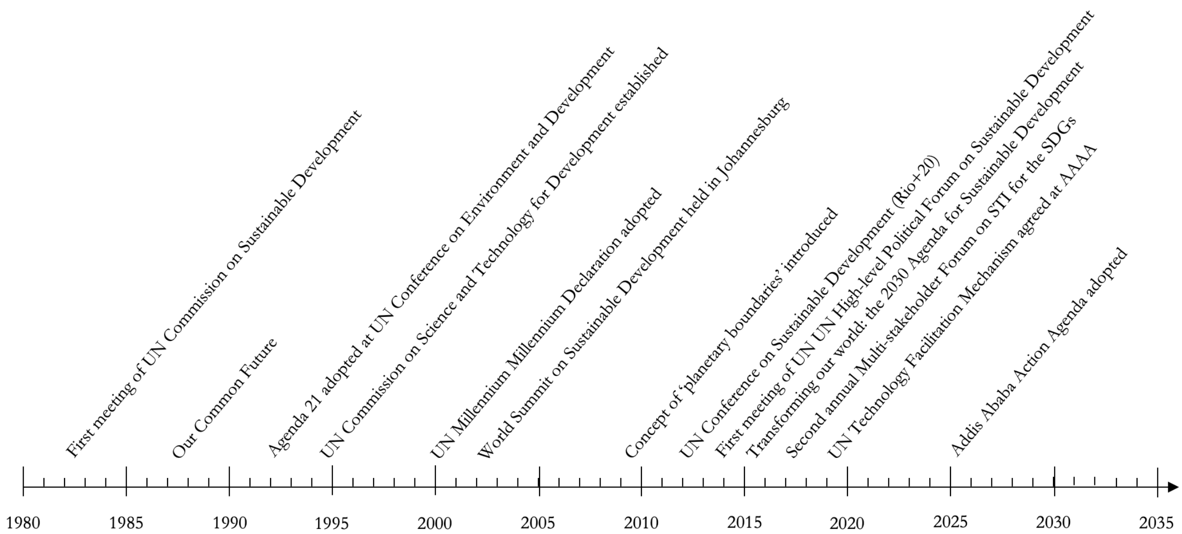

Figure 13 UN negotiations related to international cooperation for sustainable development

[90] The idea of developing a set of sustainable development goals that would be applicable to all countries emerged during the preparations for Rio+20, when Colombia proposed that one outcome from the conference should be the development of a set of Sustainable Development Goals, which would replace and supersede the UN Millennium Development Goals.

It was established as a pre-eminent body in the framework for the post-2015 development agenda, but would ultimately be responsible for the implementation and monitoring of the 2030 Agenda for Sustainable Development. The High-level Political Forum on Sustainable Development has since 2013 been the main UN platform on sustainable development. Following the thirteen sessions of the 'Open Working Group on Sustainable Development Goals' and the eight sessions of intergovernmental negotiations on the post-2015 development agenda, all of which took place between 2013 and 2015, a final text was presented by UN Secretary-General Ban Ki-moon at the Sustainable Development Summit in New York City in September 2015.

On 25 September 2015, the 194 countries of the UN adopted the 2030 Development Agenda for Sustainable Development entitled 'Transforming our world: the 2030 Agenda for Sustainable Development', which set out 17 Sustainable Development Goals that together encapsulate the major contemporary societal and environmental challenges facing the world (UN 2015:14). The universally applicable SDGs (listed in Box 5) build on the success of the Millennium Development Goals and aim to mobilise a concerted effort to end all forms of poverty, fight inequalities, and tackle climate change. A timeline of international cooperation activities under the UN in the context of sustainable development is presented in Figure 13 above.

Box 5 United Nations Sustainable Development Goals

1. *End poverty in all its forms everywhere*
2. *End hunger, achieve food security and improved nutrition, and promote sustainable agriculture*
3. *Ensure healthy lives and promote well-being for all at all ages*
4. *Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all*
5. *Achieve gender equality and empower all women and girls*
6. *Ensure availability and sustainable management of water and sanitation for all*
7. *Ensure access to affordable, reliable, sustainable and modern energy for all*
8. *Promote sustained, inclusive and sustainable economic growth, full and productive employment, and decent work*
9. *Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation*
10. *Reduce inequality within and among countries*
11. *Make cities and human settlements inclusive, safe, resilient and sustainable*
12. *Ensure sustainable consumption and production patterns*
13. *Take urgent action to combat climate change and its impacts (acknowledging that the UNFCCC is the primary international, intergovernmental forum for negotiating the global response to climate change)*
14. *Conserve and sustainably use the oceans, seas and marine resources for sustainable development*
15. *Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss*
16. *Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels*
17. *Strengthen the means of implementation and revitalize the global partnership for sustainable development*

6.7 United Nations science, technology and innovation for sustainable development

This section explores the compatibility of the integrated innovation policy framework with the United Nations Conference on Trade and Development Science, Technology and Innovation Policy Review programme and provides input to the work of the UN Technology Facilitation Mechanism established as part of the 2030 Agenda for Sustainable Development. Each case starts with a descriptive account, thereby providing a background for understanding the origin of the policy initiative in the context of science, technology and innovation for sustainable development.[91]

6.7.1 United Nations Conference on Trade and Development

The United Nations Conference on Trade and Development (UNCTAD) is the focal point of the UN on science, technology and innovation for development. The establishment of UNCTAD in 1964 was based on growing concerns of developing countries about the impacts of globalisation, multinational corporations, and the growing economic disparity between developed and developing countries. The primary objective of UNCTAD is to formulate policies relating to all aspects of development, including international trade, investment, and technology. In this way, UNCTAD provides an international forum for intergovernmental consensus building, where member states can interact freely on policy issues concerning trade and development. It performs a variety of functions, including policy and research analysis, capacity-building, and technical cooperation in developing countries. UNCTAD is a permanent intergovernmental body of the UN; it has 194 member states and is headquartered in Geneva, Switzerland.

Member states meet every four years at ministerial level to formulate policy guidelines and to set work priorities in conferences, the highest policy-making body of UNCTAD. The conference is supported in these efforts by the Trade and Development Board, which functions as the executive committee of UNCTAD. The board regularly convenes to review the activities of the secretariat and the three commissions, which meet annually in regular session to deal with policy issues relating to their area of specialisation.[92] Of particular interest to this chapter is the work of the Commission on Science and Technology for Development (CSTD); a functional commission of ECOSOC that is serviced by UNCTAD. The CSTD was established in 1993 to replace the Intergovernmental Committee on Science and Technology for Development set up at the Vienna Conference on Science and Technology for Development in 1979.

[91] See also Oldham (2006) and Standke (2006) for historical reviews of the development of science, technology and innovation policy of the UN.

[92] The three UNCTAD commissions (1) Trade and Development Commission, (2) Investment, Enterprise and Development Commission, (3) Commission on Science and Technology for Development provide the UN General Assembly and ECOSOC with high-level advice on relevant issues through analysis and appropriate policy recommendations in their respective area of expertise. Each commission may convene up to ten expert meetings a year on specific issues, and it receives scientific and technical advice from ad hoc panels and workshops that meet between sessions of the respective commission to discuss relevant issues related to science, technology and innovation for sustainable development.

Over the past decades, UNCTAD has increasingly recognised the critical role of science, technology and innovation for sustainable development. Accordingly, in 2000, UNCTAD established the Science, Technology and Innovation Policy (STIP) review programme to strengthen the innovative and technological performance of developing countries. Following the adoption of the 2030 Agenda for Sustainable Development, the CSTD has recently called on UNCTAD to revise the STIP review programme in order to address the SDGs. The first case study aims to provide an assessment of the compatibility of the integrated innovation policy framework developed in the first half of the chapter and the UNCTAD STIP review programme to legitimise policy interventions in processes of transformative change to address the SDGs.

6.7.2 UNCTAD Science, Technology and Innovation Policy Review programme

The STIP Review programme of UNCTAD is designed as an analytical and policy-learning process through which science, technology and innovation stakeholders in developing countries can gain a better understanding of the key strengths and weaknesses of their national innovation system, and identify strategic priorities and policy options for its development (UNCTAD 2011). The STIP Review programme is at the core of technical cooperation work of UNCTAD and builds on more than five decades of accumulated research experience and policy advocacy in science, technology and innovation for development. Since the STIP Review programme was established, UNCTAD has conducted 13 reviews.[93] A STIP review is a demand-driven process based on national ownership that can be divided into four phases: (1) launching the STIP review, (2) defining the terms of reference, (3) research, analysis, and preparation of the STIP report, (4) publication and dissemination of the STIP review. The process starts with an official written request to the Secretary-General of UNCTAD. High-level political commitment is critical to the success of the STIP review, and it is essential that the request is endorsed by relevant national ministries, departments, and agencies to ensure the alignment of the STIP review with national development plans and priorities. The request should designate a national counterpart with sufficient resources and support to collaborate with UNCTAD over the 12 - 18 months it typically takes to complete the STIP review.[94] The national counterpart is invited to prepare a brief report, explaining the scope, sectors, and specific questions the STIP review should cover and how it is expected to contribute to current science, technology and innovation processes in the country. If at this stage,

[93] As of June 2018, STIP reviews have been conducted in Angola, Columbia, Dominican Republic, El Salvador, Ghana, Iran, Jamaica, Lesotho, Mauritania, Oman, Peru, Rwanda, and Thailand. STIP reviews are currently conducted in Ethiopia, Sri Lanka, and Uganda while reviews in Botswana, Cameroon, Guatemala, Kenya, Moldova, and Sudan are pending subject to funding.

[94] STIP reviews are financed through extra-budgetary resources. Therefore, before a STIP can be conducted, funding for the exercise needs to be identified. The average cost of a STIP review in the region of USD 150,000.

funding for the STIP review has not been secured, the UNCTAD secretariat will assist the national counterpart in approaching potential donors in order to acquire the necessary funds.

Following the official approval, the next step in the process is to define the terms of reference, detailing the respective roles and responsibilities of UNCTAD and the national counterpart, and the scope and specific content of the STIP review including a schedule of milestones. The terms of reference serve to establish a common understanding about the objectives of the STIP review and its expected outcomes. A STIP review team is then put together and led by UNCTAD. In parallel, the national counterpart is expected to form a national STIP review group, consisting of representatives of relevant ministries, departments, agencies, and other national stakeholders, which are to help identify the major science, technology and innovation capacities and policy challenges facing the country. This assessment provides the starting point for the discussions of the STIP review team and their interactions with national stakeholders.

Once the terms of reference have been agreed and approved, an extensive review of the national innovation system is performed. Field missions, workshops, site visits, and interviews are conducted, where inputs and suggestions are collected from key national stakeholders in the country. The outcome of this consultative process is documented in a comprehensive review that, together with desk research, provides the basis for the draft report that is submitted to the national STIP review group for comments and suggestions. This a key step in the overall process. A strong effort is made to facilitate national ownership by ensuring the fullest possible involvement of national stakeholders throughout the preparation of the STIP report. The revised draft report is presented in a national workshop, which provides an opportunity to establish a broader national dialogue and to openly discuss and validate the information and receive feedback about the recommendations reflected in the STIP report. Hence, an important benefit of the national workshop is that it helps to establish a strong sense of ownership by generating consensus and 'buy-in' among policymakers and key national stakeholders on the future lines of action.

The final step of the process relates to the publication and dissemination of the STIP review. The report is published under the exclusive responsibility of UNCTAD. Its findings and recommendations are voluntary and not legally binding. Nevertheless, the STIP process is demand driven and designed to encourage strong national ownership of the outcome. The STIP review is disseminated through UNCTAD intergovernmental mechanisms such as the CSTD annual session with the engagement and participation of ministerial level representatives. This provides an appropriate forum, where government officials can give visibility among development partners and donors to its plans in the area of science, technology and innovation, and to launch concrete proposals for technical cooperation to implement the recommendations of the STIP review.

Furthermore, to ensure that the policy analysis and research are shared with the broadest audience of peers and policymakers, efforts are made to disseminate the STIP review in other appropriate forums, such as the annual sessions of the UNCTAD Investment, Enterprise and Development Commission and the Trade and Development Commission. The presentation of the findings and recommendations in the UN intergovernmental bodies completes the research, analysis, and discussion phase of the STIP review process and provide the starting point for technical cooperation and capacity-building designed to help lay the foundations for collaboration among national stakeholders to address capacity gaps identified in the STIP review.

6.7.3 Revising the STIP Review programme for the Sustainable Development Goals

Developing countries face many pressing economic development challenges, and a key concern of governments is to support the development of national productive capacities through innovation and technological change. Pursuant to the mandate and expertise of UNCTAD, the rationale of the STIP Review programme has since its establishment been to (1) strengthen national innovation systems, which in developing countries are often fragmented and still in formation and (2) integrate science, technology and innovation policy into national development plan and planning processes. Although interest in and demand for STIP reviews in developing countries has steadily increased over the past decade, UNCTAD is currently reconsidering its approach to science, technology and innovation for sustainable development. More specifically, following the adoption of the 2030 Agenda for Sustainable Development in 2015, ECOSOC called on the CSTD and the UNCTAD to revise the STIP Review programme, 'to broaden the framework for national science, technology and innovation policy reviews in order to integrate the Sustainable Development Goals …' (ECOSOC 2017:8).

On this matter, in May 2017, based on inputs from various national governments, UN agencies, and innovation systems scholars, UNCTAD released a report entitled 'New innovation approaches to support the implementation of the Sustainable Development Goals', which outlined new and emerging conceptual approaches and how these in different ways may contribute to achieving the SDGs. Although the report did not highlight the system innovation perspective, it did contain language that strongly resembled that of socio-technical systems change and the corresponding need to address transformational failures: 'The ambitious nature of the 2030 Agenda – aimed at, among others, ending poverty and reducing inequality in all its forms everywhere, to promote inclusive and sustainable consumption and production systems, to provide full and productive employment and decent work for all – will require fundamental changes in the ways in which energy, food, water, housing, welfare, mobility and other goods and services are delivered, distributed and consumed. Harnessing the positive potential for innovation to address the Sustainable Development Goals will also mean recognizing that some forms of contemporary innovation also contribute to environmental degradation, are disruptive of livelihoods and exacerbate inequalities' (2017:1).[95] This chapter suggests that to achieve the SDGs there is a need for fundamental change in the configuration of socio-technical systems towards more sustainable modes of production and consumption.[96] However, the STIP Review programme concentrates mainly on the role of firm-centred technological innovation in economic development, here largely understood as: 'a broad notion that includes not only the introduction by firms of products, marketing methods, organizational forms or productive processes that are new to the world, but also when these are new to the market or new to the firm' (UNCTAD 2011:6). An evaluation of three recent reviews confirms the STIP Review programme is mainly focused on addressing market and systemic failures to support technological innovation at the firm and industry level and not on the challenge of transforming broader systems of production and consumption (the third category of systemic problems in Table 15).[97]

The challenge going forward will be to ensure that innovation systems in developing countries prioritise the development of productive and innovative capabilities that promotes alternative economic development pathways that are socially inclusive and environmentally sustainable. Against this background, market and system failures rationales refer to the sub-optimal operation of innovation processes irrespective of any concerns about the directionality and strategic orientation of national innovation systems. Acknowledging that failure to provide an adequate policy response to contemporary societal challenges may jeopardise not only economic development but also progress made towards attaining legitimate development objectives, it is proposed that the framework upon which the STIP Review programme is built to be revised and better aligned with the 2030 Agenda for Sustainable Development. There is a need to incorporate directional innovation and a strategic orientation of innovation systems to address not only economic objectives but also a broader range of societal objectives underpinning the SDGs. In other words, the STIP Review programme should become a key systemic instrument to assess the effectiveness of science, technology and innovation policies in developing countries to identify and align strategic priories and policy options with the 2030 Agenda for Sustainable Development.

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[95] The conceptual approaches highlighted in the report were (1) mission-oriented innovation, (2) pro-poor and inclusive innovation, (3) grassroots innovation, (4) social innovation and digitally enabled open and collaborative innovation (UNCTAD 2017).

[96] See also the commission UNCTAD report entitled 'Effectively harnessing science, technology and innovation to achieve the Sustainable Development Goals' presented to the Trade and Development Board at the 2018 annual session of the Investment, Enterprise and Development Commission, which argues that 'the achievement of most Sustainable Development Goals will depend on the performance of systems for the production and delivery of food, energy, water, health care, education or transport. … The objective of STI policy aimed at tackling societal challenges is therefore to foster systemic changes with a potential for transformative impact' (UNCTAD 2018:3).

[97] This is based on the author's interpretation of the STIP reviews conducted in Thailand, Iran, and Rwanda in 2015, 2016, and 2017, respectively.

It is strongly suggested that greater consideration of the transformational failures in addition to the market and systemic failures listed in Table 15 is essential for devising coherent science, technology and innovation policies to support the type of transformative change called for in the UN 2030 Agenda for Sustainable Development. In regard to this matter, the involvement in the STIP review process of a broader and more diverse set of actors and considering demand-side conditions across economic, social, and environmental dimensions should be enhanced to collectively prioritise, coordinate, and consolidate the direction of transformative change. A more participatory approach of the STIP review processes, involving a broader and more diverse set of actors, and including social and environmental dimensions in addition to economic considerations is essential to guide the direction of innovation and processes of transformative change in socio-technical systems.[98] The following subsection proceeds by considering how the UN Technology Facilitation Mechanism plays a key role in aligning science, technology and innovation policy with the UN 2030 Agenda for Sustainable Development.

6.7.4 Towards an international platform for technology facilitation

In September 2015, three months before the adoption 2030 Agenda for Sustainable Development, members of the UN reached an agreement to launch a Technology Facilitation Mechanism (TFM) to promote coordination, coherence, and cooperation on science, technology and innovation for the SDGs. The origins of the UN TFM can be traced back to the landmark Rio+20 conference, where developing countries proposed to establish a mechanism under the UN General Assembly to address and overcome the impediments related to the long-standing dispute on how to promote, implement, and monitor concrete actions for bridging the technology gap between developed and developing countries (UN 2012). Although consensus was not reached at Rio+20, the foundation for what would eventually become the UN TFM was laid and a mandate was given in the 'The Future We Want': 'to identify options for a facilitation mechanism that promotes the development, transfer and dissemination of clean and environmentally sound technologies by, inter alia, assessing the technology needs of developing countries, options to address those needs and capacity-building' (ibid:52). Three months later, in September 2012, the UN Secretary-General launched a report entitled 'Options for a facilitation mechanism that promotes the development, transfer and dissemination of clean and environmentally sound technologies'. The report included recommendations on the possible functions and working methods of a technology facilitation mechanism and on a potential way forward to achieve improved technology facilitation.

[98] This emphasis on system innovation of socio-technical systems to the address the SDGs is at the core of revised framework for STIP reviews launched in May 2019 (UNCTAD 2019).

A series of workshops followed in 2013 to explore 'the connection between clean and environmentally sound technologies and sustainable development, taking into account the need to avoid duplication and promote synergies and coherence' (UN 2013:4). During these workshops, developing countries expressed increasing support for the creation of a technology facilitation mechanism, whereas developed countries stressed the need to avoid duplication of efforts, citing possible overlaps with the work of existing UN organisations including the UNIDO, UNCTAD, and UNEP. Building on the previous report, findings from the workshops, and written inputs received from member states, in August 2013, the UN Secretary-General issued a second report entitled 'Options for facilitating the development, transfer and dissemination of clean and environmentally sound technologies'. This report highlighted that the establishment of a UN TFM was no longer disputed by any member states; however, views differed on its mandate, functions, and institutional arrangements. Moreover, the report noted that the technology needs of developing countries had not been systematically mapped, and opinions differed significantly as to whether existing programmes and mechanisms were sufficient to meet the capacity building needs of developing countries. Finally, the report contained three groups of recommendations for improved technology facilitation including (1) initiatives that could be acted on without institutional reform of the UN system, (2) voluntary actions for consideration by member states, such as promoting national technology needs assessments, (3) more comprehensive and ambitious initiatives with institutional implications, including the creation of forums within the UN for regular expert-informed intergovernmental dialogue on how best to facilitate and enhance international technology cooperation. The third option would involve creating new or scaling up existing initiatives including (1) a technology development and transfer fund, (2) forming global networks of national organisations relevant to different stages of the technology life cycle, (3) an international network of research and innovation policymakers to discuss options for promoting international technology cooperation to address specific sustainable development challenges, (4) launching public-private partnerships to foster international technology cooperation and the transfer of technologies needed to advance progress towards addressing the SDGs.

A series of structured dialogues in 2014 further considered the possible arrangements for the UN TFM, which resulted in four concrete proposals. These were (1) better information and mapping of existing facilitation activities through an electronic knowledge platform, (2) improving coherence and synergy between existing facilitation activities including by creating an online clearinghouse of existing initiatives and networks in different thematic fields, (3) conducting further technology needs assessments in developing counties, (4) establishing a new UN TFM that would have six implementing windows including (1) a technology development fund, (2) a network of existing technology transfer, innovation, and information centres, (3) a network of universities, institutes, and research, development, and innovation institutions, (4) capacity development programmes, knowledge platforms, and technology needs assessment, (5) public-private partnerships including on intellectual property systems and licensing, (6) a management and coordination structure within the UN system including regional and sub-regional cooperative mechanisms and national coordination units. The Group of 77 and China expressed support for the fourth option, suggesting the first three options should be integral parts of the UN TFM. The EU, Japan, and the United States saw potential in the first and second option, noting that that the third option was undertaken by existing initiatives such as the UNEP CTCN.

In December 2014, the UN Secretary-General issued a report entitled 'The road to dignity by 2030: ending poverty, transforming all lives and protecting the planet' as input to the intergovernmental negotiations on the post-2015 development agenda. In this report, paragraph 125 proposed to: 'establish an online, global platform, building on and complementing existing initiatives, with the participation of all relevant stakeholders in order to: (a) map existing technology facilitation initiatives, needs and gaps, including in areas vital for sustainable development, including agriculture, cities and health; (b) enhance international cooperation and coordination in this field, addressing fragmentation and facilitating synergies, including within the UN system; and (c) promote networking, information sharing, knowledge transfer and technical assistance, in order to advance the scaling up of clean technology initiatives' (UN 2014:26).

Consensus was eventually reached in July 2015 at the Third International Conference on Financing for Development in Addis Ababa, Ethiopia, which concluded with an agreement to establish a UN TFM. Immediately after the adoption of the 'Addis Ababa Action Agenda', negotiators reconvened at UN Headquarters in New York City to complete talks on the post-2015 development agenda. Discussions on international technology cooperation during the Sustainable Development Summit focused mainly on how the 'Addis Ababa Action Agenda' paragraph 123 on the TFM should be reflected in the final outcome document. In the end, 'Transforming our World: the 2030 Agenda for Sustainable Development' fully incorporates the Addis Ababa Action Agenda agreement on the UN TFM. Specifically, paragraph 70 of 'Transforming our World: the 2030 Agenda for Sustainable Development' states: 'The Technology Facilitation Mechanism will be based on a multi-stakeholder collaboration between Member States, civil society, the private sector, the scientific community, United Nations entities and other stakeholders and will be composed of a United Nations inter-agency task team on science, technology and innovation for the Sustainable Development Goals, a multi-stakeholder forum on science, technology and innovation for the Sustainable Development Goals and an online platform' (2015:30).

6.7.5 United Nations Technology Facilitation Mechanism

The UN TFM has three main components; the first being a UN inter-agency task team on science, technology and innovation (IATT) that promotes 'coordination, coherence and cooperation within the United Nations system on science, technology and innovation-related matters, enhancing synergy and efficiency, in particular to enhance capacity-building initiatives…' (UN 2015:30).[99] The IATT is supported in these efforts by representatives from civil society, the private sector and the scientific community who provide expert advice, recommendations, and scientific guidance. Members of the so-called 'United Nations 10-Member Group to support the Technology Facilitation Mechanism' are appointed by the UN Secretary-General, for periods of two years. Each of the members have internationally recognised excellence in their field of expertise and have demonstrated an understanding of international processes related to science, technology, innovation for sustainable development. The second component is an online platform that will 'establish a comprehensive mapping of, and serve as a gateway for, information on existing science, technology and innovation initiatives, mechanisms and programmes, within and beyond the United Nations, … facilitate access to information, knowledge and experience, as well as best practices and lessons learned, on science, technology and innovation facilitation initiatives and policies [and] facilitate the dissemination of relevant open access scientific publications generated worldwide' (ibid:30). Finally, the multi-stakeholder forum on science, technology and innovation convenes once a year to discuss cooperation in science, technology and innovation around thematic areas pertaining to the implementation of the SDGs.

Drawing on synthesis between the system perspective and the systems of innovation approach, developed in the first half of the chapter, the objective of this second case study is to provide input to the work of the TFM, including its recommendations to the UN High-level Political Forum on Sustainable Development. Specifically, the aim is to engage with the vision and objectives of the UN TFM, based on the innovation policy framework developed in previous sections of the chapter, and to consider ways for policymakers and practitioners to adopt a more systemic and integrated approach towards implementing the SDGs. The case study draws mainly on official policy documents, summarising the outcomes, decisions, and lessons learned of the UN TFM, during its first three years of operation, as well as participant observations from the UN Second annual Multi-stakeholder Forum on Science, Technology and Innovation, which took place from 15-17 May 2017 at the United Nations headquarters in New York City.

[99] This includes, among other things, cooperation with the new established UN Technology Bank, which was inaugurated in 2018 in Gebze, Turkey. The task and mandate of the UN Technology Bank is to strengthen the knowledge capacity of the least developed and most vulnerable countries and identify strategic priorities and policy options to develop their national innovation systems. The Technology Bank has been the long-standing priority for least developed countries and has been supported by the UN Office of The High Representative for Least Developed Countries, Landlocked Developing Countries and Small Island Developing States since 2011.

6.7.6 Mobilising science, technology and innovation for the Sustainable Development Goals

Innovation is at the heart of political discussions on how to achieve transformative change for sustainable development. The UN TFM was established with the objective to mobilise science, technology and innovation for the SDGs and forms an essential part of the 2030 Agenda for Sustainable Development. On behalf of ECOSOC, the CSTD is encouraged 'to raise awareness among policymakers about the process of innovation and to identify particular opportunities for developing countries to benefit from such innovation, *with special attention being placed on new trends in innovation that can offer novel possibilities for developing countries*' [emphasis added] (2018:6). Referring here again to the key message of the commission report presented to the UNCTAD Trade and Development Board at the 2018 annual session of the Investment, Enterprise and Development Commission, the achievement of most, if not all, of the SDGs implies that 'STI policy will need to involve new actors, address broader concepts of innovation systems and deploy new approaches to innovation. … To take a fuller account of the potential of innovation systems for addressing the Sustainable Development Goals, an innovation systems framework to assess and develop STI policy should [therefore] include a comprehensive view of all types of innovation, new actors and partnerships, as well as a new and broader perspective on framework conditions and the environment of innovation in developing and developed countries' (UNCTAD 2018:4).

Acknowledging the mutual relationships, multiple synergies, and possible trade-offs in addressing the heterogeneity and intersectionality of the SDGs across various functional domains, a more systemic and integrated policy approach to innovation is needed to guide and consolidate the direction of transformative change. Given the expectations for the UN TFM to align science, technology and innovation with the SDGs, it is suggested here that the identification of transformational failures (as described previously in section 6.4) should be seen as a key indicator and rationale for policy intervention in the structural composition of national innovation systems.

Excerpts from the policy recommendations from the UN TFM multi-stakeholder forums to the UN High-level Political Forum on Sustainable Development clearly reflect a need to consider the transformational failures of national innovation systems to stimulate and enable system innovation of socio-technical systems: 'Science, technology and innovation are central to the advancement of the 2030 Agenda and the Goals. They will need to be responsive to the needs of the Goals and should be conceived as means of achieving them, not as ends in themselves. Not every problem has a high-technology solution, and not all technological change is conducive to sustainable development *[reflexivity failure]*. Going forward, it will be critical to assess how technology can be mobilized to provide solutions to our greatest challenges *[demand articulation* *failure]*. In that respect, various sources of knowledge, including indigenous knowledge, should be considered. All that is likely to require new ways to approach the science-policy interface. To effectively support the transformative changes implied in the 2030 Agenda, STI policy should broaden its traditional focus on targets such as productivity growth and business competitiveness to address complex societal challenges that span the economic, social and environmental dimensions of development *[policy coordination failure]*. It needs to provide a sense of direction to technological change and innovation that is consistent with sustainable and inclusive development *[directionality failure]*. STI policy should also include in its considerations both the benefits and costs of technological change and innovation. This changes the rationale of STI policy and has significant implications for STI policy strategy, instruments, processes and governance' *[italics added]* (ECOSOC 2016:56). It is suggested that to enable the transformative changes implied in the 2030 Agenda for Sustainable Development, there is need to go beyond a purely firm-centred and technology-oriented focus in innovation policy, to consider the (re)configuration of socio-technical systems towards more sustainable modes of production and consumption. It is proposed that integrating insights from the system innovation perspective to open up the systems of innovation approach by considering transformational failures, in addition to market and systemic failures, provide the necessary underpinning for innovation policy to address not only economic policy objective but also a broader range of societal and environmental objectives.

6.8 Transformative innovation policy for the Sustainable Development Goals

Since the adoption of the 2030 Agenda for Sustainable Development, the political discourse about addressing the SDGs has increasingly been framed in terms of transformative innovation that promotes economic development that is socially inclusive and environmentally sustainable. Nonetheless, as described in this and previous chapters, the systems of innovation approach – arguably the most powerful framework guiding policymakers today – is mainly directed at optimising innovation systems to fulfil economic policy objectives but largely fails to strategically orient innovation processes towards other societal and environmental objectives. There is a growing awareness that conventional patterns of innovation are insufficient to adequately deal with contemporary societal challenges and that new forms of innovation policy breaking with established practices and experiences are needed to induce transformative change (Steward 2008). A central proposition of this chapter is that innovation policy for transformative change must be grounded in an understanding of system innovation of socio-technical systems towards more sustainable modes of production and consumption. The urgent need for fundamental changes in the way societal functions are fulfilled – as implicitly called for in many of the SDGs –

demands a variety of social and technological solutions to be developed in a diverse array of sectors and diffused in a wide range of functional domains. A narrow focus on technological innovation and scientific breakthroughs, without considering necessary behavioural changes in established habits and lifestyles, is too restrictive to deal with the nature and complexity of contemporary societal challenges. To the contrary, the central premise of transformative innovation policy is that societal challenges of the type of the SDGs cannot be addressed without a fundamental change in a wide range of societal functions such as energy, food, mobility, and housing.

A synthesis between the system perspective and the systems of innovation approach provides an appropriate conceptual lens to legitimise policy interventions in processes of transformative change to address the SDGs. Hence, building on the previous sections, it is suggested that incorporating the transformational failures suggested by Weber and Rohracher (2012) in the systems of innovation approach presents a useful way forward and provides the necessary underpinning for a transformative innovation policy that is geared towards enabling system innovation of established socio-technical systems. Therefore, in addition to the conventional market and systemic failure rationales, policymakers should consider the third category of 'transformational failures' to legitimise policy interventions for transformative change in socio-technical systems. This broader and more systemic view of innovation helps to frame the scope and scale of contemporary societal challenges. It offers an integrated approach that not only incorporates the heterogeneity and intersectionality of the SDGs but also brings to light their mutual relationships, multiple synergies, and possible trade-offs (Nilsson 2016, Schot *et al.* 2018).[100] Integrating insights from the system innovation perspective in the systems of innovation approach, it is argued, challenges policymakers to rethink the SDGs around entire functional domains, rather than focusing purely on singular technological solutions. This opens up the possibility of implementing the 2030 Sustainable Development Agenda from a perspective of transformative change, where innovation serves as a cross-cutting catalyst, contributing to addressing most, if not all, the SDGs.[101] This will require new participatory approaches that 'broaden out' and 'open up' a plurality of pathways to enable cumulative distributed learning about the implications, uncertainties, and possibilities of innovation. Recent work has started to explore the complexity of these dynamics in more detail (see for instance Ely *et al.* 2014, Stirling 2014).[102]

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[100] Innovation is explicitly recognised in SDG 9 on industry, innovation, and infrastructure but is identified here as a key means of implementation that has the potential to contribute to virtually all SDGs of the UN 2030 Agenda for Sustainable Development.

[101] This agenda is at the core of the Transformative Innovation Policy Consortium (TIPC) established in 2015; a group of policy makers, practitioners, and funding agencies working together to give substance to the new framing for transformative innovation policy. Founded and coordinated by the Science Policy Research Unit (SPRU) at the University of Sussex in the United Kingdom, members comprise innovation and funding agencies from Colombia, Finland, Mexico, Norway, South Africa, and Sweden. Besides, as of May 2019, innovation agencies and other entities from Brazil, China, Ghana, the Netherlands, Panama, and Senegal are in the process of accession.

[102] As described in UNCTAD (2019) this is like to involve 'an analytic-deliberative approach utilizing formal research methods and participatory approaches to engaging stakeholders and encouraging co-creation and experimentation (e.g. transition arenas, foresight methods)' (2019:22).

7. Discussion and conclusion

The objective of this study has been to conceptually refine the systems of innovation approach, and in particular revise the framework for national innovation systems, thereby taking steps towards the development of innovation policy framework that incorporates directionality and a strategic orientation of innovation systems toward addressing contemporary societal challenges. This chapter summarises the key insights of the thesis by addressing the overall research question: *How can the systems of innovation approach be refined to incorporate a strategic orientation of innovation systems that legitimises policy interventions in processes of transformative change to address the United Nations Sustainable Development Goals?* The remainder of this chapter is organised as follows. Section 1 provides a summary of the main research findings from each of the empirical chapters, while section 2 outlines the conclusions of the research. A discussion of the policy implications of the research follows in section 3, and suggestions for future research are made in section 4.

7.1 Research findings

The empirical chapters in this thesis take different approaches to the research question addressed. Based on an actor-centred approach, chapter 4 explored how Novozymes accumulated the capabilities needed to pursue innovation in new and different directions along more sustainable development pathways, and how these interactive learning processes were influenced and conditioned by the Brazilian innovation system. Chapter 5 adopted a network-based perspective and furthered the understanding of how the formation of global innovation networks enhances interactive learning in national innovation systems, and in what way international technology cooperation complements creation and accumulation of capabilities needed to manage innovation and technological change in developing countries. Based on this understanding, chapter 6 adopted a policy perspective and, grounded in an understanding of system innovation of socio-technical systems, argued that transformative innovation policy must incorporate directionality and a strategic orientation of national innovation systems to address the nature and complexity of contemporary societal challenges of the type of the SDGs. To summarise, a central argument of this research is that the systems of innovation approach continues to provide a useful heuristic; however, it is suggested to suffer from a number of conceptual weaknesses. The core of the systems of innovation approach – the national innovation systems concept – is mainly directed at optimising the innovation system to fulfil economic policy objectives, such as growth, competitiveness, and jobs, but largely fails to guide processes of transformative change toward a broader range of societal and environmental objectives.

A first proposition of the research is that the creation and accumulation of capabilities needed to pursue innovation in significantly different directions along more sustainable development pathways are essential prerequisites for addressing the SDGs. In this regard, the strategic management literature has generated relevant insights into the STI and DUI modes of learning and how this relationship influences firm-level innovative performance. Nevertheless, most empirical studies are based on large samples of firms, and cross-sectional design and econometric analysis drawn from statistics and surveys. Although rich in conceptual and empirical approaches, these studies provide only limited evidence on the relative importance of the STI and DUI modes of learning and how this balance changes over time as firms create and accumulate innovative capabilities. Besides, most studies have been undertaken in the context of developed countries, where advanced capabilities to manage innovation and technological change typically already exist.

Attempting to unpack the complex relationship between the STI and DUI modes of learning, chapter 4 takes an actor-centred approach to analyse how Novozymes, over a 10-year period, accumulated the innovative capabilities needed to develop industrial enzyme technology for second-generation bioethanol production in Brazil. A single case study within the context of the Brazilian innovation system allowed empirical data to be collected, which is crucial to gain an in-depth understanding of the qualitative discontinuities involved in innovation capability building (see Dantas and Bell 2011, Figueiredo 2012, Kiamehr *et al.* 2015, Tokatliy 2015, Hansen *et al.* 2016 for similar methodological approaches). The study goes beyond the traditional focus on internally and externally mediated learning mechanisms and draws attention to upper levels of innovative capabilities, where latecomer firms may orchestrate processes of interactive learning derived from the interplay between science and engineering to manage innovation. Specifically, the study explores how changes to the relationship between the STI and DUI modes of learning influenced the gradual progression from intermediate to advanced innovative capabilities in Novozymes, and how these interactive learning processes were conditioned by the Brazilian innovation system.

A second proposition of the research is that interactive learning processes are increasingly enacted through the formation of global innovation networks spanning national innovation systems. National innovation systems studies have long maintained that networks of actors and institutions situated around local knowledge bases intensify interactive learning and innovation. However, considering the changing geography of innovation imposed by globalisation, there is a need to recognise that innovation processes may organise and work between and across interrelated spatial scales, and that the formation of global innovation networks works to connect and enhance processes of interactive learning between and across national innovation systems.

Chapter 5 takes a network perspective and develops a framework that differentiates global innovation networks along two dimensions: (1) mode of learning (exploration versus exploitation) and (2) organisational form (intraorganisational versus interorganisational form). Exploration refers to the development of knowledge, involving shifts to new and changing trajectories. Exploitation relates to the diffusion of knowledge along current trajectories. The exploration and exploitation of knowledge in global innovation networks taking an intraorganisational form, involve knowledge and experience in single organisations, whereas the interorganisational form refers to interactive learning through international cooperation between multiple organisations. Exploration and exploitation of knowledge in global innovation networks may contribute to strengthening the prior knowledge base of actors and organisations in national innovation systems, and to a deepening of the capabilities needed to manage innovation and technological change. The internal organisation of innovative capabilities to effectively appropriate and apply knowledge precipitates that local actors and organisations in national innovation systems have the absorptive capacity and adequate knowledge bases needed to internalise external knowledge and experience. A mapping of the growing number and variety of international cooperative initiatives in the context of climate change helps to illustrate the different forms of global innovation networks.

A third proposition of the research is that the policy paradigm for transformative change must be grounded in an understanding of socio-technical systems change towards more sustainable modes of production and consumption. However, the aspiration for directionality to improve not only economic objectives but also address a wider range of societal and environmental objectives, in many cases, conflicts with the conventional understanding of innovation as being a collective, uncertain, and cumulative process. Chapter 6 proposes to integrate insights from the system innovation perspective to open up the systems of innovation approach in order to incorporate directionality and a strategic orientation of innovation systems towards addressing the SDGs. Specifically, the chapter suggests revising the policy framework of Weber and Rohracher (2012) and incorporate elements of structural analysis to operationalise the transformational failures. Moving beyond traditional market and systemic failure rationales that impede the performance of national innovation systems, and based on the premise that innovation capability formation and new forms of collaborative network arrangements in the context of developing countries are essential means to address the SDGs, the innovation policy framework integrates the four transformational failures proposed by Weber and Rohracher (2012) in order to prioritise, coordinate, and consolidate the direction of innovation and processes of transformative change. The compatibility of the integrated policy framework is assessed with reference to the UNCTAD STIP Review programme and the UN TFM.

7.2 Research conclusions

The thesis has identified and explored three knowledge gaps that are deemed important when considering ways to refine the systems of innovation approach to incorporate directionality and a strategic orientation of innovation systems to address the SDGs. Hence, building on the three central themes of *capabilities, networks, and directionality*, each explored in the empirical chapters, the thesis takes an interdisciplinary approach towards answering the research question. This is in line with the abductive method of reasoning guiding this research to not only make an empirical contribution but also drive forward theory development. The systematic combining approach followed in the research implied that the framework for national innovation systems was continuously reoriented when confronted with the empirical world. New empirical findings suggested that theoretical influences were added to the study, while at the same time, the development of conceptual constructs influenced the direction and redirection of the research. Put another way, the critical realist position of the thesis allowed for data and theory triangulation and opened up possibilities to put the (subjective) interpretations of the world into new concepts. Moreover, importantly, systematic combining revealed that the three main research themes – *capabilities, networks, and directionality* – explored in the thesis are interdependent and closely linked and are central features of the emerging policy paradigm for transformative change.

The main conclusions of this research can be drawn at three different levels. One is about the relationship between the STI and DUI modes of learning in innovation capability building, and the limitations of the claims made regarding the STI mode of learning as the sole contributor to innovation and technological change. The second is about the changing geography of innovation imposed by globalisation, and the analytical limit of innovation systems studies to particular spatial scales. The third is about the emerging policy paradigm for transformative change and in particular about directionality as the basic premise for transformative innovation policy. The conclusions in these different areas are of course interlinked and contribute to towards answering the overall research question, and thereby provide building blocks that contribute toward the development of an innovation policy framework that incorporates directionality and a strategic orientation of innovation systems to address contemporary societal challenges.

First, the division of interactive learning between the STI and DUI learning modes explored in the thesis should ideally progress beyond linear understandings of science, technology and innovation relationships, where the output of science can be directly fed into technological development (Nightingale 1998). Previous in-depth studies have emphasised the economic importance of innovation derived from engineering and design activities and non-R&D inputs (see for instance Patel and Pavitt 1994, Laestadius 1998). Following Bell, 'given the usual focus of policy discussion on R&D as the key activities driving both the rate and direction of innovation, that assertion raises questions about the relationship between design and engineering (D&E) on the one hand and R&D on the other, and in particular about the knowledge-base that D&E activities draw on in playing their creative innovation role' (2009:33).

Chapter 4 draws attention to the intra-organisational dimension concerning the relationship between science and engineering and how changes to this relationship influence the upper levels of innovation capability in latecomer firms. While most research on the interplay between STI and DUI modes of learning has focused on firm-level innovation performance in developed countries, the chapter shows that such a perspective can provide analytical leverage in relation to the catching up of latecomer firms in developing countries. In the context of the Brazilian innovation system, the findings of an in-depth qualitative case study suggest that the gradual progression from intermediate to advanced innovation capabilities in Novozymes was shaped significantly by changes to the relationship between the STI and DUI modes of learning over a 10-year period. It was found that in the early period between 2007 and 2011, intermediate innovative capabilities were built mainly from practical technical problem-solving, whereas science-based learning gained importance relative to experience-based learning, mainly through improved testing and experimentation in the research laboratories, during the progression to advanced innovative capabilities between 2012 and 2016. Hence, as a deliberate effort was made to determine new methods of developing customer-specific solutions based on local market conditions and raw material characteristics in Brazil, science-based learning gained relative importance as Novozymes needed to appropriate the knowledge necessary to anticipate a variety of application conditions, and to understand the technological parameters influencing the second-generation bioethanol production process. Put differently, experience-based learning from practical technical problem-solving and user-producer interaction in the Brazilian innovation system, in the early period of experimental development, constituted a logical sequence for the accumulation of the knowledge base that provided Novozymes with a sense of opportunity and potential of its enzyme technology, Cellic CTec. The gradual accumulation and build-up of knowledge, in turn, allowed Novozymes to improve testing and experimentation in the research laboratories in the later phase of applied research, thereby gaining a better understanding of the different stages of bioethanol production.

Clearly, a division between the appropriation and application of knowledge masks a more complex and diverse set of interactive learning activities in innovation capability accumulation. Nonetheless, a division between the two processes is considered useful to illustrate the interplay between science-based and experience-based learning in latecomer firms, and the limitations of the claims made regarding the STI mode of learning as the main contributor to innovation and technological change. On the contrary, the empirical findings of an in-depth qualitative case study for the Brazilian subsidiary of the global biotechnology company, Novozymes, suggest that in the early stages of firm-level innovation capability building, experience-based learning play a more dominant role, whereas, in the later stages, science-based learning gains relative importance. It follows that innovation and technological change, and the capabilities needed to manage these, need to be appreciated as more than a narrow portrayal of 'commercialisation of science', as not all innovation is science-based and purely STI-driven. Rather, innovation and technological change involve iteratively moving from known to unknown configurations; that is, an interactive learning process characterised by the interplay between science and engineering.

Second, the analytical limit of innovation systems studies to particular spatial scales seems increasingly less appropriate considering the changing geography of innovation. Innovation scholars are calling that the globalisation of innovation is clarified to develop more accurate interpretations of contemporary innovation processes (Grillitsch and Trippl 2014, Martin 2016, Weber and Truffer 2017). Chapter 5, based on the insights gained from the previous chapter, develops an understanding of how the formation of global innovation networks connects and enhances processes of interactive learning in national innovation systems and in what way international technology cooperation may complement the formation of innovation capabilities in developing countries. Building in particular on the recent work of Binz and Truffer (2017), chapter 5 proposes a framework that differentiates between the exploration and exploitation of knowledge in global innovation networks and how international technology cooperation may contribute to strengthening the prior knowledge base of local actors and organisations in national innovation systems, and may contribute to a deepening of innovation capabilities through the subsequent use of technology that extends beyond routine operations to enable a series of cumulative innovation and technological change. This circular dynamic implies that international technology cooperation does not work without the presence of local innovation capabilities, but at the same time, the formation of global innovation networks can complement the development of these capabilities (Bell 2009). Hence, reiterating here the central message of Fu *et al.* (2011), the role of technology transfer in innovation capability building in developing countries cannot be understood in isolation because external knowledge and experience derived from the formation of global innovation networks are complementary aspects that are combined in the creation and accumulation of capabilities needed to manage innovation and technological change.

By way of exploring how and in what way international technology cooperation complements innovation capability formation in developing countries, the mapping of ten innovation intermediaries brings to light the complementarity between the growing number and variety of international cooperative initiatives that have emerged over the past decades to address the challenge of climate change. On the one hand, international cooperative initiatives, including as Mission Innovation and the IEA TCPs focus on the exploration of knowledge along new or shifting trajectories in the early stages of the innovation cycle in order to accelerate and achieve cost-effective scientific breakthroughs in energy technologies with a variety of potential applications. One the other hand, innovation intermediaries such as the UNFCCC CTCN, Cleaner Energy Ministerial, and WBIN concentrate on the exploitation of knowledge along current technological trajectories in the later stages of the innovation cycle and seek to accelerate the large-scale demonstration and deployment of environmental sound technologies.

Third, it is increasingly recognised that current rationales for innovation policy are insufficient to address the nature and complexity and contemporary societal challenges, such as poverty, inequality, and climate change. The systems of innovation approach is mainly directed at optimising national innovation systems to fulfil economic policy objectives, such as growth, competitiveness, and jobs but largely fails to incorporate directionality and a strategic orientation of innovation systems toward a broader range of societal and environmental objectives. The frame of reference has changed following the adoption of the UN 2030 Agenda for Sustainable Development and with it, the requirements for conceptual approaches that underpin innovation policy. Chapter 6 proposes to revise the policy framework of Weber and Rohracher (2012) and incorporates elements of structural analysis that allows devising transformative innovation policy that explicitly incorporates directionality and a strategic orientation of national innovation systems. Based on the premise that innovation capability formation and new forms of collaborative network arrangements are essential means to address the SDGs, the chapter suggests that next to the conventional market and systemic failures that impede the performance of innovation systems, there is a need to incorporate the four transformational failures proposed by Weber and Rohracher (2012) in the systems of innovation approach in order to collectively prioritise, coordinate, and consolidate the direction of innovation and processes of transformative change. An assessment of the UNCTAD STIP Review programme and UN TFM found that these capacity building initiatives are primarily focused on addressing market and systemic failures of national innovation systems to support technological innovation at the firm and industry level and not on the challenge of transforming socio-technical systems of production and consumption.

In conclusion, this research suggests that to incorporate a strategic orientation of innovation systems that legitimises policy interventions in processes of transformative change to address the SDGs, there is a need to consider the central features of *capabilities, networks, and directionality*. Each explored in turn, the individual chapters of the thesis give empirical support that; first, innovation capability formation, particularly in the context of developing countries, to support significantly different directions of innovation along more sustainable development pathways, is an essential prerequisite for addressing the SDGs. Second, these interactive learning processes are not necessarily spatially bounded, but work between and across interrelated spatial scales and are increasingly enacted through the formation of global innovation networks spanning national innovation systems. Third, moving beyond traditional market and systemic failure rationales that impede the performance of national innovation systems, there is a need to consider transformational failures in order to prioritise, coordinate, and consolidate the direction of innovation and processes of transformative change in socio-technical systems. Notwithstanding these findings, in order to arrive at a fully integrated policy framework that explicitly incorporates directionality and a strategic orientation of innovation systems to address contemporary societal and environmental challenges, more research is needed than what can be achieved in a single thesis.

7.3 Implications for transformative innovation policy

The thesis ends with some broader implications for transformative innovation policy, personal reflections about the emerging policy paradigm, and some suggestions for a future research agenda. Since the adoption of the 2030 Agenda for Sustainable Development, the political discourse about addressing the SDGs has increasingly been framed in terms of transformative innovation that promotes economic growth that is socially inclusive and environmentally sustainable (Diercks *et al.* 2019). However, despite growing research in this field, there is still a poor understanding of the possible refinements to the systems of innovation approach that are needed to design transformative innovation policy. The broader policy implications of this research follow from several observations in the empirical chapters, which can be shifted to create at least some wider space for thinking about the emerging policy paradigm for transformative change.

Concerning the first proposition of the thesis about *capabilities*, a focus on interactive learning in innovation capability formation draws attention away from science, technology and innovation, and emphasises the importance of design and engineering activities. Although the balance and interplay between the STI and DUI modes of learning may seem obvious, this complementarity is often overlooked in favour of STI mode. Interactive learning as determinant for innovation capability building has implications for transformative innovation policy in at least two respects. First, the tendency to fall back on policy measures like science and technology parks, subsidies and loans, and matching grants as well as fiscal and tax incentives to promote R&D in public and private sector organisations in developing countries is widespread. However, such policy measures are often poorly oriented towards the conditions in developing countries, where innovation systems are fragmented and emerging. Innovation capabilities do not result from science-based learning and processes of R&D alone but equally from engineering and experience-based learning; that is, an interactive learning process derived from the interplay between the STI and DUI modes of learning. In the early phases of national innovation systems, innovative capabilities are mainly built from practical technical problem solving encountered in the interactions between users and producers. Only after national innovation systems have developed more advanced capabilities to manage innovation and technological change, do the STI mode of learning start to play a more influential role. In this respect, considerable attention should be paid to strengthening design and engineering capabilities in developing countries, for instance, through technical and vocational education systems that provide science, technology, engineering and mathematics (STEM) skills.

A second implication is that a focus on interactive learning processes in developing countries must be based on the broad and evolutionary view of national innovation systems promoted by Lundvall and others (see for instance Chaminade and Padilla-Pérez 2017, Chaminade *et al.* 2018). A singular focus on the advancement and maturing of high-tech sectors and industries, emphasising science-driven innovation and R&D activities based on formal STI relationships, risks overlooking important interstices, determinants, and dynamics that influence innovation, interactive learning, and capacity building in developing countries. A broader and more inclusive view of the national innovation system, comprising not only firms and knowledge institutes, operating in professional design and production environments, but essentially all parts and aspects of society, including the informal economy, as far as these have an impact on innovation, need to be considered in transformative innovation policy (see definition provided in Box 2).

With respect to the second proposition of the thesis about *networks*, the suggestion that interactive learning processes are increasingly enacted and connected through the formation of global innovation networks does not mean to imply that external knowledge and experience occur automatically. As described in the previous chapters, innovation capabilities are built from the combination of absorptive capacity and interactive learning. This dynamism may accrue or diminish over time, depending on the extent to which deliberate and continuous efforts are made to sustain it. However, with notable exceptions (see for instance TEC 2015, IPCC 2018), the narrow view of technology transfer (as described in subsection 5.4.6) is discernible in numerous policy reports, particularly in the context of climate change. The narrow view pays little attention to the presence of innovative capabilities as an essential precondition to effectively optimise and adapt technology transferred to local conditions. This is despite the fact that a critical insight to emerge from the literature on national innovation systems in developing countries is that 'for countries aiming to catch up, developing the capabilities for learning and innovation in firms is at the heart of the challenge' (Nelson 2011:48). The broader view, on the other hand, generally considers the presence of capabilities needed to manage innovation and technological change as a necessary prerequisite for international technology cooperation; that is, the process is inherently contingent on actors and organisations having the adequate knowledge bases and absorptive capacity to effectively appropriate and apply external knowledge and experience.

The role of international technology cooperation to address the challenge of climate change can therefore hardly be understood in isolation, because the external knowledge and experiences derived from the formation of global innovation networks are complementary aspects that are combined in innovation capability building (Fu *et al.* 2011). To put it bluntly, the policy implications of this is that 'technology can be "transferred" only in a very narrow sense and only provided that one adopts a narrow and outdated notion of technology development, learning and innovation. Capabilities are *built* and *acquired* rather than *transferred*' (Lema and Lema 2012:39).

To provide a comprehensive policy response to address the challenge of climate change, clearly, there is a need for intermediation across all stages of the innovation cycle. Nonetheless, considering the central message of the IPCC (2018), that keeping to the preferred target of 1.5 degrees Celsius above pre-industrial levels involves 'rapid, far-reaching and unprecedented changes in all aspects of society' to enable the global transition to a low-carbon society over the next decade, it may be that developing countries are better served by demand-driven structures that focus on delivering targeted capability building through technical assistance, training programmes, and information sharing activities to support the active demonstration and deployment of proven technologies. Since this research understands the challenge to address climate change in the context of developing countries as more related to the deployment of existing technologies rather than the R&D of new technologies, the author is largely sympathetic towards enhancing international technology cooperation that targets the later stages of the innovation cycle to complement the capabilities needed to accelerate large-scale technology deployment. Based on the premise that the presence of innovation capabilities in developing countries is a necessary prerequisite to effectively optimise and adapt technology to local conditions, it is therefore essential that international technology cooperation captures all three flows of knowledge and experience listed in subsection 5.3.1 (see also Bell 2012, Lema and Lema 2012, Watson *et al.* 2014).

Regarding the third proposition about *directionality*, the central premise of this research is that conventional innovation policy is concerned mainly with economic policy objectives and do not express a clear preference for growth that is socially inclusive and environmentally sustainable. Consequently, a core proposition of this research is that the systems of innovation approach requires conceptual refinement in order to incorporate directionality and a strategic orientation of innovation systems towards a broader range of societal and environmental objectives. This 'normative' turn towards transformative innovation policy must be grounded in an understanding of system innovation of socio-technical systems towards more sustainable modes of production and consumption. The implications of this is that to address the SDGS, there is a need for fundamental changes in the way societal functions are fulfilled. A narrow focus on firm-centred technology-mediated change without considering necessary behavioural changes in established habits and lifestyles is too restrictive to deal with societal challenges, such as poverty, inequality, and climate change. To the contrary, the central premise of this research is that societal challenges of the type of the SDGs requires more than scientific breakthroughs and technological innovation. The type of transformative change called for in the UN 2030 Agenda for Sustainable Development demands a variety of social and technological solutions to be developed in an array of sectors and diffused in a wide range of functional domains. Put differently, transformative innovation policy calls for stimulating and enabling socio-technical systems change.

7.4 Future research agenda

This final section can be very brief because, as pointed out by Diercks *et al.,* 'transformative innovation policy is only emerging, and the next years will be crucial in institutionalising its core ideas, concepts, and categories that will inform a limited amount of more structured and established policy practice' (2019:892). It is often suggested that socio-technical systems in developing countries are less 'locked-in' to unsustainable pathways, opening up important opportunities for 'environmental leapfrogging' and catching-up (Watson and Sauter 2011). Certainly, a key point to emerge from the literature is the need to destabilise established socio-technical systems to create windows of opportunity for niche configurations to emerge (Geels and Schot 2007). On the other hand, sustainability transition studies in developing countries also show that unstable and highly dynamic regimes can create barriers for niche development (see for instance Verbong *et al.* 2010). A certain degree of regime stability, therefore, seems to be needed for successful niche breakthroughs, at least in the context of developing countries (this hypothesis was initially developed in Raven 2005). But that is entirely speculation, or rather, it is a call for more research to understand better socio-technical systems change in the context of developing countries. We know very little about sustainability transitions in the global South and the literature has until recently been scarce and underdeveloped (see Hansen *et al.* 2018, Wieczorek 2018 for reviews of this literature). Besides, there has been almost no analysis of transformative innovation policy in developing countries, although important work is underway (TIPC 2019). I hope the work presented in this thesis encourages more research in this direction.

References

Abdel-Latif, A., 2015. Intellectual property rights and the transfer of climate change technologies: Issues, challenges, and way forward. *Climate Policy*, 15 (1), 103–126.

Adcock, R. and Collier, D., 2001. Measurement validity: A shared standard for qualitative and quantitative research. *American Political Science Review*, 95 (3), 529–546.

Aggarwal, A., 2001. Technology policies and acquisition of technological capabilities in the industrial sector: A comparative analysis of the Indian and Korean experiences. *Science, Technology and Society*, 6 (2), 255–304.

Allard, G., Martinez, C.A., and Williams, C., 2012. Political instability, pro-business market reforms and their impacts on national systems of innovation. *Research Policy*, 41 (3), 638–651.

Almeida, J.R.M., Modig, T., Petersson, A., Hähn-Hägerdal, B., Lidén, G., and Grauslund, M.F.G., 2007. Increased tolerance and conversion of inhibitors in lignocellulosic hydrolysates by Saccharomyces cerevisiae. *Journal of Chemical Technology & Biotechnology*, 82 (4), 340–349.

Altenburg, T., 2009. Building inclusive innovation systems in developing countries: Challenges for IS research. *In*: B.-A Lundvall, K.J. Joseph, and C. Chaminade, eds. *Handbook of innovation systems and developing countries: Building domestic capabilities in a global setting*. Cheltenham, United Kingdom: Edward Elgar Publishing, 33–56.

Alvesson, M. and Sandberg, J., 2011. Generating research questions through problematization. *Academy of Management Review*, 36 (2), 247–271.

Amable, B. and Hancké, B., 2001. Innovation and industrial renewal in France in comparative perspective. *Industry and Innovation*, 8 (2), 113–133.

Amsden, A.H. and Tschang, F.T., 2003. A new approach to assessing the technological complexity of different categories of R&D (with examples from Singapore). *Research Policy*, 32 (4), 553–572.

Andersen, A.D., 2011. *Innovation systems and natural resources: The case of sugarcane in Brazil*. Aalborg, Denmark: Aalborg University.

Andersen, A.D., 2015. A functions approach to innovation system building in the 'South': The evolution of the sugarcane and biofuel industry in Brazil. *Innovation and Development*, 5 (1), 1–21.

Andersson, U., Forsgren, M., and Holm, U., 2002. The strategic impact of external networks: Subsidiary performance and competence development in the multinational corporation. *Strategic Management Journal*, 23, 979–996.

Araújo, W.A., 2016. Ethanol industry: surpassing uncertainties and looking forward. *In*: S.L.M. Salles-Filho, L.A.B. Cortez, J.M.F.J. Silveira, S.C. Trindade, and M.G.D. Fonseca, eds. *Global bioethanol: Evolution, risks, and uncertainties*. London, United Kingdom: Elsevier, 1–33.

Archibugi, D., Howells, J., and Michie, J., 1999. Innovation systems in a global economy. *Technology Analysis & Strategic Management*, 11 (4), 527–539.

Archibugi, D. and Iammarino, S., 1999. The policy implications of the globalisation of innovation. *Research Policy*, 28 (2–3), 317–336.

Archibugi, D. and Michie, J., 1995. The globalisation of technology: A new taxonomy. *Journal of Economics*, 19 (1), 121–140.

Argote, L. and Ingram, P., 2000. Knowledge transfer: A basis for competitive advantage in firms. *Organizational Behavior and Human Decision Processes*, 82 (1), 150–169.

Ariffin, N. and Figueiredo, P.N., 2004. Internationalization of innovative capabilities: Counter-evidence from the electronics industry in Malaysia and Brazil. *Oxford Development Studies*, 32 (4), 559–583.

Arocena, R. and Sutz, J., 2000. Looking at national systems of innovation from the South. *Industry and Innovation*, 7 (1), 55–75.

Arthur, B.W., 1989. Competing technologies, increasing returns, and lock-in by historical events. *The Economic Journal*, 99 (394), 116–131.

Arundel, A., Lorenz, E., Lundvall, B.-A., and Valeyre, A., 2007. How Europe's economies learn: A comparison of work organization and innovation mode for the EU-15. *Industrial and Corporate Change*, 16 (6), 1175–1210.

Asheim, B.T. and Coenen, L., 2005. Knowledge bases and regional innovation systems: Comparing Nordic clusters. *Research Policy*, 34 (8), 1173–1190.

Asheim, B.T. and Gertler, M.S., 2006. The geography of innovation: Regional innovation systems. *In*: J. Fagerberg, D.C. Mowery, and R.R. Nelson, eds. *The Oxford handbook of innovation*. London, United Kingdom: Oxford University Press, 291–317.

Asheim, B.T. and Isaksen, A., 2002. Regional innovation systems: The integration of local 'sticky' and global 'ubiquitous' knowledge. *Journal of Technology Transfer*, 27 (1), 77–86.

Aslesen, H.W., Isaksen, A., and Karlsen, J., 2012. Modes of innovation and differentiated responses to globalization: A case study of innovation modes in the Agder region, Norway. *Journal of the Knowledge Economy*, 3 (4), 389–405.

Attia, A.M., 2015. National innovation systems in developing countries: Barriers to university–industry collaboration in Egypt. *International Journal of Technology Management & Sustainable Development*, 14 (2), 113–124.

Balat, M., Balat, H., and Öz, C., 2008. Progress in bioethanol processing. *Progress in Energy and Combustion Science*, 34 (5), 551–573.

Balzat, M. and Hanusch, H., 2004. Recent trends in the research on national innovation systems. *Journal of Evolutionary Economics*, 14 (2), 197–210.

Barnard, H. and Chaminade, C., 2017. Openness of innovation systems through global innovation networks: A comparative analysis of firms in developed and emerging economies. *International Journal of Technological Learning, Innovation and Development*, 9 (3), 269–292.

Bartels, F.L., Voss, H., Lederer, S., and Bachtrog, C., 2012. Determinants of national innovation systems: Policy implications for developing countries. *Innovation*, 14 (1), 2–18.

Basant, R. and Chandra, P., 2007. Role of educational and R&D institutions in city clusters: An exploratory study of Bangalore and Pune regions in India. *World Development*, 35 (6), 1037–1055.

Bathelt, H., Malmberg, A., and Maskell, P., 2004. Clusters and knowledge: Local buzz, global pipelines and the process of knowledge creation. *Progress in Human Geography*, 28 (1), 31–56.

van Beers, C., Berghäll, E., and Poot, T., 2008. R&D internationalization, R&D collaboration and public knowledge institutions in small economies: Evidence from Finland and the Netherlands. *Research Policy*, 37 (2), 294–308.

Bell, M., 1984. 'Learning' and the accumulation of industrial capacity in developing countries. *In*: F. Martin and K. King, eds. *Technological capability in the third world*. London, United Kingdom: Palgrave Macmillan, 187–209.

Bell, M., 2009. *Innovation capabilities and directions of development*. STEPS Working Paper (33). Brighton, United Kingdom: STEPS Centre.

Bell, M., 2012. International technology transfer, innovation capabilities and sustainable directions of development. *In*: D.G. Ockwell and A. Mallett, eds. *Low-carbon technology transfer: From rhetoric to reality*. London, United Kingdom: Routledge, 20–50.

Bell, M. and Figueiredo, P.N., 2012. Innovation capability building and learning mechanisms in latecomer firms: Recent empirical contributions and implications for research. *Canadian Journal of Development Studies*, 33 (1), 14–40.

Bell, M. and Pavitt, K., 1993. Technological accumulation and industrial growth: Contrasts between developed and developing countries. *Industrial and Corporate Change*, 2 (1), 157–210.

Bell, M. and Pavitt, K., 1995. The development of technological capabilities. *In*: I.U. Haque, ed. *Trade, technology and international competitiveness*. Washington DC, United States: World Bank, 69–101.

Benner, M.J. and Tushman, M.L., 2003. Exploitation, exploration, and process management: The productivity dilemma revisited. *The Academy of Management Review*, 28 (2), 238–256.

Bergek, A., Hekkert, M.P., Jacobsson, S., Markard, J., Sandén, B.A., and Truffer, B., 2015. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. *Environmental Innovation and Societal Transitions*, 16, 51–64.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., and Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37 (3), 407–429.

Berkhout, F., Angel, D., and Wieczorek, A.J., 2009. Asian development pathways and sustainable socio-technical regimes. *Technological Forecasting and Social Change*, 76 (2), 218–228.

Bessant, J. and Rush, H., 1995. Building bridges for innovation: The role of consultants in technology transfer. *Research Policy*, 24 (1), 97–114.

Bhaskar, R., 1975. *A realist theory of science*. London, United Kingdom: Verso.

Bijker, W.E., Hughes, T.P., and Pinch, T.J., 1987. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, Massachusetts, United States: MIT Press.

Binz, C., and Truffer, B., 2017. Global innovation systems: A conceptual framework for innovation dynamics in transnational contexts. *Research Policy*, 46 (7), 1284–1298.

Binz, C., Truffer, B., and Coenen, L., 2014. Why space matters in technological innovation systems: Mapping global knowledge dynamics of membrane bioreactor technology. *Research Policy*, 43 (1), 138–155.

Birkinshaw, J.M., Hood, N., and Jonsson, S., 1998. Building firm-specific advantages in multinational corporations: The role of subsidiary initiative. *Strategic Management Journal*, 19, 221–241.

Blumer, H., 1954. What is wrong with social theory? *American Sociological Review*, 19 (1), 3–10.

Boon, W. and Edler, J., 2018. Demand, challenges, and innovation. Making sense of new trends in innovation policy. *Science and Public Policy*, 45 (4), 435–447.

Boon, W.P.C., Moors, E.H.M., Kuhlmann, S., and Smits, R.E.H.M., 2011. Demand articulation in emerging technologies: Intermediary user organisations as co-producers? *Research Policy*, 40 (2), 242–252.

Bordonal, R.O., Lal, R., Alves Aguiar, D., De Figueiredo, E.B., Ito Perillo, L., Adami, M., Theodor Rudorff, B.F., and La Scala, N., 2015. Greenhouse gas balance from cultivation and direct land use change of recently established sugarcane (saccharum officinarum) plantation in south-central Brazil. *Renewable and Sustainable Energy Reviews*, 52, 547–556.

Borrás, S. and Edquist, C., 2019. *Holistic innovation policy: Theoretical foundations, policy problems, and instrument choices*. London, United Kingdom: Oxford University Press.

Boschma, R., 2005. Proximity and innovation: A critical assessment. *Regional Studies*, 39 (1), 61–74.

Brasileiro, B.P., Marinho, C.D., Costa, P.M.A., Moreira, E.F.A., Peternelli, L.A., and Barbosa, M.H.P., 2014. Genetic diversity in sugarcane varieties in Brazil based on the ward-modified location model clustering strategy. *Genetics and Molecular Research*, 13 (1), 1650–1660.

Breschi, S. and Malerba, F., 1997. Sectoral innovation systems: Technological regimes, Schumpeterian dynamics, and spatial boundaries. *In*: C. Edquist, ed. *Systems of innovation: Technologies, institutions and organizations*. London, United Kingdom: Pinter, 130–156.

Breznitz, D., 2005. Collaborative public space in a national innovation system: A case study of the Israeli military's impact on the software industry. *Industry & Innovation*, 12 (1), 31–64.

Brundtland, G.H., 1987. *Our common future*. London, United Kingdom: Oxford University Press.

Bryman, A., 2015. *Social research methods*. London, United Kingdom: Oxford University Press.

Buckeridge, M.S. and Souza, A.P., 2017. *Advances of basic science for second generation bioethanol from sugarcane*. London, United Kingdom: Springer.

Burhan, M., Singh, A.K., and Jain, S.K., 2017. Patents as proxy for measuring innovations: A case of changing patent filing behavior in Indian public funded research organizations. *Technological Forecasting and Social Change*, 123, 181–190.

Bush, V., 1945. *Science the endless frontier*. Washington DC, United States: United States Government Printing Office.

Callon, M., 1987. Society in the making. *In*: W.E. Bijker, T.P. Hughes, and T.J. Pinch, eds. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, Massachusetts, United States: MIT Press, 83–103.

Callon, M., 1991. Techno-economic networks and irreversibility. *In*: J. Law, ed. *A sociology of monsters: Essays on power technology, and domination*. London, United Kingdom: Routledge, 132–161.

Cantwell, J. and Mudambi, R., 2005. MNE competence-creating subsidiary mandates. *Strategic Management Journal*, 26, 1109–1128.

Caraça, J., Lundvall, B.-Å., and Mendonça, S., 2009. The changing role of science in the innovation process: From queen to Cinderella? *Technological Forecasting and Social Change*, 76 (6), 861–867.

Carayannis, E.G. and Campbell, D.F.J., 2009. 'Mode 3' and 'quadruple helix': Toward a 21st century fractal innovation ecosystem. *International Journal of Technology Management*, 46 (3–4), 201–234.

Carlsson, B. and Jacobsson, S., 1997. In search of useful public policies: Key lessons and issues for policy makers. *In*: B. Carlsson, ed. *Technological systems and industrial dynamics*. Boston, Massachusetts, United States: Springer, 299–315.

Carlsson, B., Jacobsson, S., Holmén, M., and Rickne, A., 2002. Innovation systems: Analytical and methodological issues. *Research Policy*, 31 (2), 233–245.

Carlsson, B. and Stankiewicz, R., 1991. On the nature, function and composition of technological systems. *Journal of Evolutionary Economics*, 1 (2), 93–118.

Carson, R., 1962. *Silent spring*. Boston, Massachusetts, United States: Houghton Mifflin Harcourt.

Castellacci, F., 2009. The interactions between national systems and sectoral patterns of innovation. *Journal of Evolutionary Economics*, 19 (3), 321–347.

CEM, 2016. Framework for the Clean Energy Ministerial (CEM) [online]. Available from: www.cleanenergyministerial.org [Accessed 5 Oct 2018].

CEM, 2017. Clean Energy Ministerial [online]. Available from: www.cleanenergyministerial.org [Accessed 18 Dec 2017].

CGIAR, 2017. Consultative Group for International Agricultural Research [online]. Available from: www.cgiar.org [Accessed 18 Dec 2017].

Chaminade, C. and Edquist, C., 2010. Rationales for public policy intervention in the innovation process: Systems of innovation approach. *In*: R.E. Smits, S. Kuhlmann, and P. Shapira, eds. *The theory and practice of innovation policy: An international research handbook*. London, United Kingdom: Edward Elgar Publishing, 95–114.

Chaminade, C., Intarakumnerd, P., and Sapprasert, K., 2012. Measuring systemic problems in national innovation systems: An application to Thailand. *Research Policy*, 41 (8), 1476–1488.

Chaminade, C., Lundvall, B.-A., and Haneef, S., eds., 2018. *Advanced introduction to national innovation systems*. London, United Kingdom: Edward Elgar Publishing.

Chaminade, C. and Padilla-Pérez, R., 2017. The challenge of alignment and barriers for the design and implementation of science, technology and innovation policies for innovation systems in developing countries. *In*: S. Kuhlmann and G. Ordóñez-Matamoros, eds. *Research handbook on innovation governance for emerging economies: Towards better models*. Cheltenham, United Kingdom: Edward Elgar Publishing, 181–204.

Chaminade, C. and Perez, R.P.P., 2014. *The challenge of alignment and barriers for the design and implementation of science, technology and innovation policies for innovation systems in developing countries*. Papers in Innovation Studies (26). Lund, Sweden: CIRCLE.

Chaminade, C. and Plechero, M., 2015. Do regions make a difference? Regional innovation systems and global innovation networks in the ICT industry. *European Planning Studies*, 23 (2), 215–237.

Chaminade, C. and Vang, J., 2008. Globalisation of knowledge production and regional innovation policy: Supporting specialized hubs in the Bangalore software industry. *Research Policy*, 37 (10), 1684–1696.

Chen, K. and Kenney, M., 2007. Universities/research institutes and regional innovation systems: The cases of Beijing and Shenzhen. *World Development*, 35 (6), 1056–1074.

Chen, S.-H., 2007. The national innovation system and foreign R&D: The case of Taiwan. *R&D Management*, 37 (5), 441–453.

Ciera, X. and Maloney, W.F., 2017. *The Innovation paradox: Developing-country capabilities and the unrealized promise of technological catch-up*. Washington DC, United States: World Bank.

Coenen, L., Benneworth, P., and Truffer, B., 2012. Toward a spatial perspective on sustainability transitions. *Research Policy*, 41 (6), 968–979.

Coenen, L., Hansen, T., and Rekers, J. V., 2015. Innovation policy for grand challenges: An economic geography perspective. *Geography Compass*, 9 (9), 483–496.

Cohen, W.M. and Levinthal, D.A., 1990. Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterley*, 35 (1), 128–152.

Coninck, H. d., Fischer, C., Newell, R.G., and Ueno, T., 2008. International technology-oriented agreements to address climate change. *Energy Policy*, 36 (1), 335–356.

Coninck, H. and Sagar, A.D., 2015. Making sense of policy for climate technology development and transfer. *Climate Policy*, 15 (1), 1–11.

Cooke, P., 2003. *Strategies for regional innovation systems: Learning transfer and applications*. Geneva, Switzerland: United Nations Industrial Development Organization.

Cooke, P., Uranga, M.G.-, and Goio, E., 1997. Regional innovation systems: Institutional and organisational dimensions. *Research Policy*, 26 (4–5), 475–491.

Correa, C.M., 1998. Argentina's national innovation system. *International Journal of Technology Management*, 15 (6–7), 721–760.

Cortez, L.A.B., 2010. *Sugarcane bioethanol: R&D for productivity and sustainability*. São Paulo, Brazil: Edgard Blucher.

Crespi, G. and Zuniga, P., 2012. Innovation and productivity: Evidence from six Latin American countries. *World Development*, 40 (2), 273–290.

Crespo, N. and Fontoura, M.P., 2007. Determinant factors of FDI spillovers: What do we really know? *World Development*, 35 (3), 410–425.

CSLF, 2003. Charter for the Carbon Sequestration Leadership Forum (CSLF): A carbon capture and storage technology initiative [online]. Available from: www.cslforum.org [Accessed 18 Dec 2017].

CSLF, 2017. Communiqué of the 7th ministerial meeting of the Carbon Sequestration Leadership Forum [online]. Available from: www.cslforum.org [Accessed 18 Dec 2017].

CTCN, 2013. Prioritization criteria for responding to requests from developing country parties [online]. Available from: www.ctc-n.org [Accessed 12 Dec 2017].

Dahlström, M. and James, L., 2012. Regional policies for knowledge anchoring in European regions. *European Planning Studies*, 20 (11), 1867–1887.

Daimer, S., Hufnagl, M., and Warnke, P., 2012. Challenge-oriented policy-making and innovation systems theory: Reconsidering systemic instruments. *In*: K. Koschatzky, ed. *Innovation systems revisited: Experiences from 40 years of Fraunhofer ISI research*. Stuttgart, Germany: Fraunhofer Verlag, 217–234.

Danermark, B., Ekström, M., Jakobsen, L., and Karlsson, J.C., 2002. *Explaining society: Critical realism in the social sciences*. London, United Kingdom: Routledge.

Dantas, E. and Bell, M., 2011. The co-evolution of firm-centered knowledge networks and capabilities in late industrializing countries: The case of Petrobras in the offshore oil innovation system in Brazil. *World Development*, 39 (9), 1570–1591.

David, P.A., 1985. Clio and the economics of QWERTY. *The American Economic Review*, 75 (2), 332–337.

Delvenne, P. and Thoreau, F., 2012. Beyond the "charmed circle" of OECD: New directions for studies of national innovation systems. *Minerva*, 50 (2), 205–219.

Denzin, N.K. and Lincoln, Y.S., 2005. *The SAGE handbook of qualitative research*. London, United Kingdom: Sage Publications.

Dessai, S., Adger, N.W., Hulme, M., and Turnpenny, J., 2004. Defining and experiencing dangerous climate change. *Climatic Change*, 64 (1), 11–25.

Dewar, R.D. and Dutton, J.E., 1986. The adoption of radical and incremental innovations: An empirical analysis. *Management Science*, 32 (11), 1422–1433.

Dias, M.O.S., Junqueira, T.L., Cavalett, O., Cunha, M.P., Jesus, C.D.F., Rossell, C.E. V, Maciel Filho, R., and Bonomi, A., 2012. Integrated versus stand-alone second-generation ethanol production from sugarcane bagasse and trash. *Bioresource Technology*, 103 (1), 152–161.

Diercks, G., 2017. *Transformative innovation policy: Assessing discourse institutionalisation of an emerging policy paradigm*. London, United Kingdom: Imperial College London.

Diercks, G., Larsen, H., and Steward, F., 2019. Transformative innovation policy: Addressing variety in an emerging policy paradigm. *Research Policy*, 48 (4), 880–894.

Disco, C., Rip, A., and Meulen B., 1992. Technical innovation and the universities: Divisions of labour in cosmopolitan technical regimes. *Social Science Information*, 31 (3), 465–507.

Dodgson, M., Mathews, J., Kastelle, T., and Hu, M.-C., 2008. The evolving nature of Taiwan's national innovation system: The case of biotechnology innovation networks. *Research Policy*, 37 (3), 430–445.

Dosi, G., 1982. Technological paradigms and technological trajectories: A suggested interpretation of the determinants and directions of technical change. *Research Policy*, 11 (3), 147–162.

Dosi, G., 1988. Sources, procedures, and microeconomic effects of innovation. *Journal of Economic Literature*, 26 (3), 1120–1171.

Dubois, A. and Gadde, L.-E., 2002. Systematic combining: An abductive approach to case research. *Journal of Business Research*, 55 (7), 553–560.

Dubois, A. and Gadde, L.E., 2014. Systematic combining: A decade later. *Journal of Business Research*, 67 (6), 1277–1284.

Dutrénit, G., 2000. *Learning and knowledge management in the firm: From knowledge accumulation to strategic capabilities*. London, United Kingdom: Edward Elgar Publishing.

Dutrénit, G. and Sutz, J., 2014. *National systems of innovation: Social inclusion and development: The Latin American experience*. London, United Kingdom: Edward Elgar Publishing.

Easterby-Smith, M., Thorpe, R., and Jackson, P., 2008. *Management research: Theory and practice*. London, United Kingdom: Sage Publications.

EC, 2013. *Europe 2020: Europe's growth strategy*. Brussels, Belgium: European Commission.

EC, 2018. *Missions: Mission-oiented research & innovation in the European Union: A problem-solving approach to fuel innovation-led growth*. Brussels, Belgium: European Commission.

Edler, J. and Georghiou, L., 2007. Public procurement and innovation: Resurrecting the demand side. *Research Policy*, 36 (7), 949–963.

Edler, J. and Yeow, J., 2016. Connecting demand and supply: The role of intermediation in public procurement of innovation. *Research Policy*, 45 (2), 414–426.

Edquist, C., 1997. *Systems of innovation: Technologies, institutions and organizations*. London, United Kingdom: Pinter.

Edquist, C., 2006. Systems of innovation: Perspectives and challenges. *In*: J. Fagerberg, D.C. Mowery, and R.R. Nelson, eds. *The Oxford handbook of innovation*. London, United Kingdom: Oxford University Press, 181–208.

Edquist, C. and Zabala-Iturriagagoitia, J.M., 2012. Public procurement for innovation as mission-oriented innovation policy. *Research Policy*, 41 (10), 1757–1769.

Edquist, C., Zabala-iturriagagoitia, J.M., Barbero, J., and Zofío, J.L., 2018. On the meaning of innovation performance: Is the synthetic indicator of the Innovation Union scoreboard flawed? *Research Evaluation*, 27 (3), 196–211.

EEA, 2017. *Perspectives on transitions to sustainability*. Copenhagen, Denmark: European Environmental Agency.

Ehrlich, P.R., 1968. *The population bomb*. London, United Kingdom: Buccaneer Books.

Eisenhardt, K.M., 1989. Building theories from case study research. *Academy of Management Review*, 14 (4), 532–550.

Eisenhardt, K.M. and Graebner, M.E., 2007. Theory building from cases: Opportunities and challenges. *Academy of Management*, 50 (1), 25–32.

Eisenhardt, K.M. and Martin, J.A., 2000. Dynamic capabilities: What are they? *Strategic Management Journal*, 21 (10–11), 1105–1121.

Elkington, J., 2018. 25 years ago I coined the phrase "triple bottom line": Here's why it's time to rethink it. *Harvard Business Review*, 25 June 2018.

Ely, A., Smith, A., Stirling, A., Leach, M., and Scoones, I., 2013. Innovation politics post-Rio+20: Hybrid pathways to sustainability. *Environment and Planning C: Government and Policy*, 31 (6), 1063–1081.

Ely, A., Van Zwanenberg, P., and Stirling, A., 2014. Broadening out and opening up technology assessment: Approaches to enhance international development, co-ordination and democratisation. *Research Policy*, 43 (3), 505–518.

Elzen, B., Geels, F.W., and Green, K., eds., 2004. *System innovation and the transition to sustainability: Theory, evidence and policy*. London, United Kingdom: Edward Elgar Publishing.

Emerson, R.M., Fratz, R.I., and Shaw, L.L., 2001. Participant observation and field notes. *In*: P. Atkinson, S. Delamont, A. Coffey, J. Lofland, and L. Lofland, eds. *Handbook of ethnography*. London, United Kingdom: Sage Publications, 352–368.

Eom, B.-Y. and Lee, K., 2010. Determinants of industry–academy linkages and, their impact on firm performance: The case of Korea as a latecomer in knowledge industrialization. *Research Policy*, 39 (5), 625–639.

Etzkowitz, H. and Leydesdorff, L., 2000. The dynamics of innovation: From national systems and "mode 2" to a triple helix of university–industry–government relations. *Research Policy*, 29 (2), 109–123.

Fagerberg, J., 2006. Innovation: A guide to the literature. *In*: J. Fagerberg, D.C. Mowery, and R.R. Nelson, eds. *The Oxford handbook of innovation*. London, United Kingdom: Oxford University Press, 1–27.

Fagerberg, J., Mowery, D.C., and Nelson, R.R., eds., 2006. *The Oxford handbook of innovation*. London, United Kingdom: Oxford University Press.

Fagerberg, J., Mowery, D.C., and Verspagen, B., 2009. The evolution of Norway's national innovation system. *Science and Public Policy*, 36 (6), 431–444.

Fagerberg, J. and Sapprasert, K., 2011. National innovation systems: The emergence of a new approach. *Science and Public Policy*, 38 (9), 669–679.

Fagerberg, J. and Srholec, M., 2008. National innovation systems, capabilities and economic development. *Research Policy*, 37 (9), 1417–1435.

Fan, P., 2011. Innovation capacity and economic development: China and India. *Economic Change and Restructuring*, 44 (1–2), 49–73.

Feinson, S., 2003. National innovation systems overview and country cases. *In*: *Knowledge flows and knowledge collectives: Understanding the role of science and technology policies in development*. New York City, New York, United States: Rockefeller Foundation, 13–38.

Felker, G. and Sundaram, J.K., 2007. Technology policy in Malaysia. *International Journal of Technological Learning, Innovation and Development*, 1 (2), 153.

Fereday, J. and Muir-Cochrane, E., 2006. Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development. *International Journal of Qualitative Methods*, 5 (1), 80–92.

Fernández-Esquinas, M. and Ramos-Vielba, I., 2011. Emerging forms of cross-sector collaboration in the Spanish innovation system. *Science and Public Policy*, 38 (2), 135–146.

Fernández, J. and Gavilanes, J.C., 2017. Learning-by-importing in emerging innovation systems: Evidence from Ecuador. *The Journal of International Trade & Economic Development*, 26 (1), 45–64.

Figueiredo, P.N., 2001. *Technological learning and competitive performances*. London, United Kingdom: Edward Elgar Publishing.

Figueiredo, P.N., 2002. Does technological learning pay off? Inter-firm differences in technological capability-accumulation paths and operational performance improvement. *Research Policy*, 31 (1), 73–94.

Figueiredo, P.N., 2003. Learning, capability accumulation and firms differences: Evidence from latecomer steel. *Industrial and Corporate Change*, 12 (3), 607–643.

Figueiredo, P.N., 2011. The role of dual embeddedness in the innovative performance of MNE Subsidiaries: Evidence from Brazil. *Journal of Management Studies*, 48 (2), 417–440.

Figueiredo, P.N., 2012. Embedding with multiple knowledge sources to improve innovation performance: The learning experience of Motorola in Brazil. *Knowledge Management Research & Practice*, 11 (4), 361–373.

Figueiredo, P.N., 2017. Micro-level technological capability accumulation in developing economies: Insights from the Brazilian sugarcane ethanol industry. *Journal of Cleaner Production*, 167, 416–431.

Figueiredo, P.N. and Cohen, M., 2019. Explaining early entry into path-creation technological catch-up in the forestry and pulp industry: Evidence from Brazil. *Research Policy*, 48 (7), 1694–1713.

Fischer, M.M., 2001. Innovation, knowledge creation and systems of innovation. *The Annals of Regional Science*, 35 (2), 199–216.

Flyvbjerg, B., 2006. Five misunderstandings about case-study research. *Qualitative Inquiry*, 12 (2), 219–245.

Foray, D., Mowery, D.C., and Nelson, R.R., 2012. Public R&D and social challenges: What lessons from mission R&D programs? *Research Policy*, 41 (10), 1697–1702.

Foxon, T.J. and Pearson, P.J.G., 2008. Overcoming barriers to innovation and diffusion of cleaner technologies: Some features of a sustainable innovation policy regime. *Journal of Cleaner Production*, 16, 148–161.

Franco, E., Ray, S., and Ray, P.K., 2011. Patterns of innovation practices of multinational-affiliates in emerging economies: Evidences from Brazil and India. *World Development*, 39 (7), 1249–1260.

Frantzeskaki, N., Broto, V.C., Coenen, L., and Loorbach, D., eds., 2017. *Urban sustainability transitions*. London, United Kingdom: Routledge.

Freeman, C., 1982. *Technological infrastructure and international competitiveness*. Paris, France: Organisation for Economic Co-operation and Development.

Freeman, C., 1987. *Technology policy and economic performance: Lessons from Japan*. London, United Kingdom: Pinter.

Freeman, C., 1992. *The economics of hope: Essays on technical change, economic growth, and the environment*. London, United Kingdom: Thomson Learning.

Freeman, C., 1995. The 'national system of innovation' in historical perspective. *Cambridge Journal of Economics*, 19 (1), 5–24.

Freeman, C., 2002. Continental, national and sub-national innovation systems: Complementarity and economic growth. *Research Policy*, 31 (2), 191–211.

Freeman, C. and Perez, C., 1988. Structural crisis of adjustment, business cycles and investment behaviour. *In*: G. Dosi, C. Freeman, R.R. Nelson, G. Silverberg, and L. Soete, eds. *Technical change and economic theory*. London, United Kingdom: Pinter, 38–66.

Freeman, C. and Soete, L., 1997. *The economics of industrial innovation*. London, United Kingdom: Routledge.

Fromhold-Eisebith, M., 2007. Bridging scales in innovation policies: How to link regional, national and international innovation systems. *European Planning Studies*, 15 (2), 217–233.

Fu, X., Pietrobelli, C., and Soete, L., 2011. The role of foreign technology and indigenous innovation in the emerging economies: Technological change and catching-up. *World Development*, 39 (7), 1204–1212.

Fu, X. and Zhang, J., 2011. Technology transfer, indigenous innovation and leapfrogging in green technology: The solar-PV industry in China and India. *Journal of Chinese Economic and Business Studies*, 9 (4), 329–347.

Furman, J.L. and Hayes, R., 2004. Catching up or standing still? National innovative productivity among 'follower' countries, 1978-1999. *Research Policy*, 33 (9), 1329–1354.

Furman, J.L., Porter, M.E., and Stern, S., 2002. The determinants of national innovative capacity. *Research Policy*, 31 (6), 899–933.

Furtado, A.T., Scandiffio, M.I.G., and Cortez, L.A.B., 2011. The Brazilian sugarcane innovation system. *Energy Policy*, 39 (1), 156–166.

Gale, N.K., Heath, G., Cameron, E., Rashid, S., and Redwood, S., 2013. Using the framework method for the analysis of qualitative data in multi-disciplinary health research. *BMC Medical Research Methodology*, 13 (1), 117.

Gámez, S., González-Cabriales, J.J., Ramírez, J.A., Garrote, G., and Vázquez, M., 2006. Study of the hydrolysis of sugar cane bagasse using phosphoric acid. *Journal of Food Engineering*, 74 (1), 78–88.

Garud, R. and Karnøe, P., 2003. Bricolage versus breakthrough: Distributed and embedded agency in technology entrepreneurship. *Research Policy*, 32 (2), 277–300.

Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research Policy*, 31 (8–9), 1257–1274.

Geels, F.W., 2004. From sectoral systems of innovation to socio-technical systems: Insights about dynamics and change from sociology and institutional theory. *Research Policy*, 33 (6–7), 897–920.

Geels, F.W., 2011. The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions*, 1 (1), 24–40.

Geels, F.W. and Schot, J., 2007. Typology of sociotechnical transition pathways. *Research Policy*, 36 (3), 399–417.

Ghazinoory, S. and Ghazinoori, S., 2006. Developing Iran's government strategies for strengthening the national system of innovation using SWOT analysis. *Science and Public Policy*, 33 (7), 529–540.

Gibson, C.B. and Birkinshaw, J., 2004. The antecedents, consequences, and mediating role of organizational ambidexterity. *The Academy of Management Journal*, 47 (2), 209–226.

Giuliani, E. and Bell, M., 2005. The micro-determinants of meso-level learning and innovation: Evidence from a Chilean wine cluster. *Research Policy*, 34 (1), 47–68.

Giuliani, E., Gorgoni, S., Günther, C., and Rabellotti, R., 2014. Emerging versus advanced country MNEs investing in Europe: A typology of subsidiary global-local connections. *International Business Review*, 23 (4), 680–691.

Glaser, B.G., 1978. *Theoretical sensitivity: Advances in the methodology of grounded theory*. London, United Kingdom: The Sociology Press.

Godin, B., 2009. National innovation system: The system approach in a historical perspective. *Science, Technology, & Human Values*, 34 (4), 476–501.

Godinho, M.M. and Ferreira, V., 2012. Analyzing the evidence of an IPR take-off in China and India. *Research Policy*, 41 (3), 499–511.

Goldemberg, J., 2007. Ethanol for a sustainable energy future. *Science*, 315 (5813), 808–810.

Goldemberg, J., 2013. Sugarcane ethanol: Strategies to a successful program in Brazil. *In*: J.W. Lee, ed. *Advanced biofuels and bioproducts*. London, United Kingdom: Springer, 13–20.

Gosens, J., Lu, Y., and Coenen, L., 2015. The role of transnational dimensions in emerging economy 'technological innovation systems' for clean-tech. *Journal of Cleaner Production*, 86, 378–388.

Grillitsch, M. and Trippl, M., 2014. Combining knowledge from different sources, channels and geographical scales. *European Planning Studies*, 22 (11), 2305–2325.

Grin, J., Rotmans, J., and Schot, J., 2010. *Transitions to sustainable development: New directions in the study of long term transformative change*. London, United Kingdom: Routledge.

Grupp, H. and Schubert, T., 2010. Review and new evidence on composite innovation indicators for evaluating national performance. *Research Policy*, 39 (1), 67–78.

Gu, S. and Lundvall, B.-A., 2006. China's innovation system and the move toward harmonious growth and endogenous innovation. *Innovation: Management, Policy & Practice*, 8 (1), 1–26.

Guan, J. and Chen, K., 2012. Modelling the relative efficiency of national innovation systems. *Research Policy*, 41 (1), 102–115.

Gulati, R., Nohria, N., and Zaheer, A., 2000. Strategic networks. *Strategic Management Journal*, 21 (3), 203–215.

Gunderson, L.H. and Holling, C.S., 2001. *Panarchy: Understanding transformations in human and natural systems*. Washington DC, United States: Island Press.

Gupta, A.K. and Govindarajan, V., 2000. Knowledge flows within multinational corporations. *Strategic Management Journal*, 22 (4), 473–496.

Gupta, A.K., Smith, K.G., and Shalley, C.E., 2006. The interplay between exploration and exploitation. *Academy of Management Journal*, 49 (4), 693–706.

Haakonsson, S.J. and Slepniov, D., 2018. Technology transmission across national innovation systems: The role of Danish suppliers in upgrading the wind energy industry in China. *The European Journal of Development Research*, 30 (3), 462–480.

Haakonsson, S.J. and Ujjual, V., 2015. Internationalisation of R&D: New insights into multinational enterprises' R&D strategies in emerging markets. *Management Revue*, 26 (2), 101–122.

Hajer, M.A., Nilsson, M., Raworth, K., Bakker, P., Berkhout, F., de Boer, Y., Rockström, J., Ludwig, K., and Kok, M., 2015. Beyond cockpit-ism: Four insights to enhance the transformative potential of the sustainable development goals. *Sustainability*, 7 (February), 1651–1660.

Hall, A., Bockett, G., Taylor, S., Sivamohan, M.V.., and Clark, N., 2001. Why research partnerships really matter: Innovation theory, institutional arrangements and implications for developing new technology for the poor. *World Development*, 29 (5), 783–797.

Hall, J., Matos, S., Silvestre, B., and Martin, M., 2011. Managing technological and social uncertainties of innovation: The evolution of Brazilian energy and agriculture. *Technological Forecasting and Social Change*, 78 (7), 1147–1157.

Hamel, G., 1991. Competition for competence and inter-partner learning within international strategic alliances. *Strategic Management Journal,* 12, 83–103.

Hansen, T. and Coenen, L., 2015. The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental Innovation and Societal Transitions*, 17, 92–109.

Hansen, U.E. and Ockwell, D.G., 2014. Learning and technological capability building in emerging economies: The case of the biomass power equipment industry in Malaysia. *Technovation*, 34 (10), 617–630.

Hansen, U.E., Fold, N., and Hansen, T., 2016. Upgrading to lead firm position via international acquisition: Learning from the global biomass power plant industry. *Journal of Economic Geography*, 16 (1), 131–153.

Hansen, U.E. and Lema, R., 2019. The co-evolution of learning mechanisms and technological capabilities: Lessons from energy technologies in emerging economies. *Technological Forecasting & Social Change*, 140 (3), 141–257.

Hansen, U.E., Nygaard, I., Romijn, H., Wieczorek, A., Kamp, L.M., and Klerkx, L., 2018. *Sustainability transitions in developing countries: Stocktaking, new contributions and a research agenda*. Environmental Science & Policy, 84, 198–203.

Hargadon, A. and Sutton, R., 1997. Technology brokering and innovation in a product development firm. *Administrative Science Quarterley*, 42 (4), 718–749.

Harvey, M. and Bharucha, Z.P., 2016. Political orientations, state regulation, and biofuels in the context of the food-energy-climate change trilemma. *In*: S.L.M. Salles-Filho, L.A.B. Cortez, J.M.F.J. Silveira, and S.C. Trindade, eds. *Global bioethanol: Evolution, risks, and uncertainties*. London, United Kingdom: Elsevier, 63–92.

Hay, C., 2007. Does ontology trump epistemology? Notes on the directional dependence of ontology and epistemology in political analysis. *Politics*, 27 (2), 115–118.

He, Z.-L. and Wong, P.-K., 2004. Exploration vs. exploitation: An empirical test of the ambidexterity hypothesis. *Organization Science*, 15 (4), 481–494.

Hekkert, M.P., Suurs, R., Negro, S.O., Kuhlmann, S., and Smits, R., 2007. Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74 (4), 413–432.

Hendriks, A.T.W.M. and Zeeman, G., 2009. Pretreatments to enhance the digestibility of lignocellulosic biomass. *Bioresource Technology*, 100 (1), 10–18.

Hernández-Salas, J.M., Villa-Ramírez, M.S., Veloz-Rendón, J.S., Rivera-Hernández, K.N., González-César, R.A., Plascencia-Espinosa, M.A., and Trejo-Estrada, S.R., 2009. Comparative hydrolysis and fermentation of sugarcane and agave bagasse. *Bioresource Technology*, 100 (3), 1238–1245.

Herstad, S.J., Aslesen, H.W., and Ebersberger, B., 2014. On industrial knowledge bases, commercial opportunities and global innovation network linkages. *Research Policy*, 43 (3), 495–504.

den Hertog, P., 2000. Knowledge-intensive business services as co-producers of innovation. *International Journal of Innovation Management*, 4 (4), 491–528.

Hickel, J., 2019. The contradiction of the sustainable development goals: Growth versus ecology on a finite planet. *Sustainable Development*.

von Hippel, E. V., 1998. *Sources of innovation*. London, United Kingdom: Oxford University Press.

Hobday, M., 1995. *Innovation in East Asia: The challenge to Japan*. London, United Kingdom: Edward Elgar Publishing.

Holmqvist, M., 2004. Experiential learning processes of exploitation and exploration within and between organizations: An empirical study of product development. *Organization Science*, 15 (1), 70–81.

Hong, W., 2008. Decline of the center: The decentralizing process of knowledge transfer of Chinese universities from 1985 to 2004. *Research Policy*, 37 (4), 580–595.

Hu, A.G.Z. and Jefferson, G.H., 2008. Science and technology in China. *In*: L. Brandt and T.G. Rawski, eds. *China's great economic transformation*. Cambridge, Massachusetts, United States: Cambridge University Press, 286–336.

Hughes, T.P., 1983. *Networks of power: Electrification in Western society, 1880 - 1930*. Baltimore, Maryland, United States: Johns Hopkins University Press.

Hughes, T.P., 1987. The evolution of large technological systems. *In*: W.E. Bijker, T.P. Hughes, and T.J. Pinch, eds. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, Massachusetts, United States: MIT Press, 51–82.

Hulme, M., 2009. *Why we disagree about climate change: Understanding controversy, inaction and opportunity*. Cambridge, Massachusetts, United States: Cambridge University Press.

Hung, S.-C. and Whittington, R., 2011. Agency in national innovation systems: Institutional entrepreneurship and the professionalization of Taiwanese IT. *Research Policy*, 40 (4), 526–538.

Hyett, N., Kenny, A., Dickson-Swift, V., Dickson-Swift, V., and Dr, 2014. Methodology or method? A critical review of qualitative case study reports. *International Journal of Qualitative Studies on Health and Well-being*, 9, 23606.

IEA, 2003. IEA framework for international energy technology co-operation (framework)* [online]. Available from: www.iea.org [Accessed 5 Oct 2018].

IEA, 2014. *Mapping multilateral collaboration on low-carbon energy technologies*. Paris, France: International Energy Agency.

IEA, 2016. *Technology Collaboration Programmes: Highlights and outcomes*. Paris, France: International Energy Agency.

IEA, 2017. *Energy access outlook 2017: From poverty to prosperity*. Paris, France: International Energy Agency.

IEA, 2019. *Tracking SDG7: The energy progress report*. Paris, France: International Energy Agency.

Intarakumnerd, P., Chairatana, P., and Tangchitpiboon, T., 2002. National innovation system in less successful developing countries: The case of Thailand. *Research Policy*, 31 (8–9), 1445–1457.

IPBES, 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Bonn, Germany: Intergovernmental Platform for Biodiversity and Ecosystem Services.

IPCC, 2000. *Methodological and technological issues in technology transfer*. Geneva, Switzerland: Intergovernmental Panel on Climate Change.

IPCC, 2014. *Climate change 2014: Synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Bonn, Germany: Intergovernmental Panel on Climate Change.

IPCC, 2018. *Global warming of 1.5 °C: An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*. Incheon, South Korea: Intergovernmental Panel on Climate Change.

IPEEC, 2008. Declaration International Partnership for Energy Efficiency [IPEEC] [online]. Available from: www.g8.utoronto.ca [Accessed 5 Oct 2018].

IRENA, 2009. Statute of the International Renewable Energy Agency (IRENA) [online]. Available from: www.irena.org [Accessed 5 Oct 2018].

IRENA, 2017. International Renewable Energy Agency [online]. Available from: www.irena.org [Accessed 5 Oct 2018].

ISA, 2015. Framework agreement on the establishment of the International Solar Alliance (ISA) [online]. Available from: www.isolaralliance.org [Accessed 5 Oct 2018].

ISA, 2019. International Solar Alliance [online]. Available from: www.isolaralliance.org [Accessed 5 Oct 2018].

Isaksen, A. and Karlsen, J., 2012. Combined and complex modes of innovation in regional cluster development. *In*: B.T. Asheim and M.D. Parrilli, eds. *Interactive Learning for Innovation*. London, United Kingdom: Palgrave Macmillan, 115–135.

Isaksen, A. and Nilsson, M., 2013. Combined innovation policy: Linking scientific and practical knowledge in innovation systems. *European Planning Studies*, 21 (12), 1919–1936.

Jensen, M.B., Johnson, B., Lorenz, E., and Lundvall, B.-Å., 2007. Forms of knowledge and modes of innovation. *Research Policy*, 36 (5), 680–693.

Johnson, B. and Gregersen, B., 1995. Systems of innovation and economic integration. *Journal of Industry Studies*, 2 (2), 1–18.

Joly, P., Callon, M., and Rip, A., 2010. Reinventing innovation. *In*: M. Arentsen, ed. *Governance and innovation*. London, United Kingdom: Edward Elgar Publishing, 19–32.

Jung, J. and Mah, J.S., 2013. R&D policies of Korea and their implications for developing countries. *Science, Technology and Society*, 18 (2), 165–188.

Kaiser, R. and Prange, H., 2004. The reconfiguration of national innovation systems: The example of German biotechnology. *Research Policy*, 33 (3), 395–408.

Kang, K.-N. and Park, H., 2012. Influence of government R&D support and inter-firm collaborations on innovation in Korean biotechnology SMEs. *Technovation*, 32 (1), 68–78.

Katila, R. and Ahuja, G., 2002. Something old, something new: A longitudinal study of search behavior and new product introduction. *The Academy of Management Journal*, 45 (6), 1183–1194.

Katz, J. and Pietrobelli, C., 2018. Natural resource based growth, global value chains and domestic capabilities in the mining industry. *Resources Policy*, 58, 11–20.

Kemp, R., Loorbach, D., and Rotmans, J., 2007. Transition management as a model for managing processes of co-evolution towards sustainable development. *International Journal of Sustainable Development & World Ecology*, 14 (1), 78–91.

Kemp, R., Schot, J., and Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: The approach of strategic niche management. *Technology Analysis & Strategic Management*, 10 (2), 175–198.

Kern, F., Kuzemco, C., and Mitchell, C., 2014. Measuring and explaining policy paradigm change. *Policy & Politics*, 42 (4), 513–530.

Khanna, M., Scheffran, J., and Zilberman, D., eds., 2009. *Handbook of bioenergy economics and policy*. London, United Kingdom: Springer.

Kiamehr, M., Hobday, M., and Hamedi, M., 2015. Latecomer firm strategies in complex product systems (CoPS): The case of Iran's thermal electricity generation systems. *Research Policy*, 44 (6), 1240–1251.

Kilduff, M., 2006. Editor's comments: Publishing theory. *Academy of Management Review*, 31 (2), 252–255.

Kim, L., 1997. *Imitation to innovation: The dynamics of Korea's technological learning*. Cambridge, Massachusetts, United States: Harvard Business School Press.

Kim, L., 1998. Crisis construction and organizational learning: Capability building in catching-up at Hyundai Motor. *Organization Science*, 9 (4), 506–521.

Kim, Y., Lee, B., and Lim, Y., 1999. A comparative study of managerial features between public and private R&D organisations in Korea: Managerial and policy implications for public R&D organisations. *International Journal of Technology Management*, 17 (3), 281.

King, D., Browne, J., Layard, R., O'Donnell, G., Rees, M., Stern, N., and Turner, A., 2015. *A global Apollo programme to combat climate change*. London, United Kingdom.

Kivimaa, P., 2014. Government-affiliated intermediary organisations as actors in system-level transitions. *Research Policy*, 43 (8), 1370–1380.

Kivimaa, P., Boon, W., Hyysalo, S., and Klerkx, L., 2019. Towards a typology of intermediaries in sustainability transitions: A systematic review and a research agenda. *Research Policy*, 48 (4), 1062–1075.

Kivimaa, P. and Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. *Research Policy*, 45 (1), 205–217.

Klerkx, L. and Aarts, N., 2013. The interaction of multiple champions in orchestrating innovation networks: Conflicts and complementarities. *Technovation*, 33 (6–7), 193–210.

Klerkx, L., Álvarez, R., and Campusano, R., 2015. The emergence and functioning of innovation intermediaries in maturing innovation systems: The case of Chile. *Innovation and Development*, 5 (1), 73–91.

Klerkx, L. and Leeuwis, C., 2008. Delegation of authority in research funding to networks: Experiences with a multiple goal boundary organization. *Science and Public Policy*, 35 (3), 183–196.

Klerkx, L. and Leeuwis, C., 2009. Establishment and embedding of innovation brokers at different innovation system levels: Insights from the Dutch agricultural sector. *Technological Forecasting and Social Change*, 76 (6), 849–860.

Kline, S.J., 1995. *Conceptual foundations for multi-disciplinary thinking*. Stanford, California, United States: Stanford University Press.

Kline, S.J. and Rosenberg, N., 1986. An overview of innovation. *In*: R. Landau and N. Rosenberg, eds. *The positive sum strategy: Harnessing technology for economic growth*. Washington DC, United States: National Academy Press, 275–305.

Kogut, B. and Zander, U., 1992. Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization Science*, 3 (3), 383–397.

Kolodny, H., Stymne, B., Shani, R., Figuera, J.R., and Lillrank, P., 2001. Design and policy choices for technology extension organizations. *Research Policy*, 30 (2), 201–225.

Kruss, G. and Lorentzen, J., 2009. The South African innovation policies: Potential and constraint. *In*: J. Cassiolato, ed. *BRICS and development alternatives: Innovation systems and policies*. London, United Kingdom: Anthem Press, 163–190.

Kuemmerle, W., 1999. Foreign direct investment in industrial research in the pharmaceutical and electronics industries: Results from a survey of multinational firms. *Research Policy*, 28 (2–2), 179–193.

Kuhlmann, S. and Rip, A., 2014. The challenge of addressing grand challenges. *Research Europe*, 1–11.

Kuhlmann, S. and Rip, A., 2018. Next-generation innovation policy and grand challenges. *Science and Public Policy*, 45 (4), 448–454.

Kvale, S., 1996. *InterViews: An introduction to qualitative research interviewing*. London, United Kingdom: Sage Publications.

Laestadius, S., 1998. The relevance of science and technology indicators: The case of pulp and paper. *Research Policy*, 27 (4), 385–395.

Lakitan, B., 2013. Connecting all the dots: Identifying the "actor level" challenges in establishing effective innovation system in Indonesia. *Technology in Society*, 35 (1), 41–54.

Lall, S., 1992. Technological capabilities and industrialization. *World Development*, 20 (2), 165–186.

Lall, S. and Pietrobelli, C., 2005. National technology systems in Sub-Saharan Africa. *International Journal of Technology and Globalisation*, 1 (3–4), 311–342.

Landell, M.G.D.A., Pinto, L.R., Creste, S., Chabregas, S.M., and Burnquist, W.L., 2014. TRM: Genetic breeding and biotechnology component. *In*: L.A.B. Cortez, ed. *Sugarcane bioethanol - R&D for productivity and sustainability*. São Paulo: Edgard Blucher, 883–896.

Lane, P.J. and Lubatkin, M., 1998. Relative absorptive capacity and interorganizational learning. *Strategic Management Journal*, 19 (5), 461–477.

Larsson, R., Bengtsson, L., and Henriksson, K., 1998. The interorganizational learning dilemma: Collective knowledge development in strategic alliances. *Organization*, 9 (3), 285–305.

Laschewski, L., Phillipson, J., and Gorton, M., 2002. The facilitation and formalisation of small business networks: Evidence from the north east of England. *Environment and Planning C: Government and Policy*, 20 (3), 375–391.

Latour, B., 1987. *Science in action: How to follow scientists and engineers through society*. Cambridge, Massachusetts, United States: Harvard University Press.

Lavie, D., Stettner, U., and Tushman, M.L., 2010. Exploration and exploitation within and across organizations. *Academy of Management Annals*, 4 (1), 109–155.

Law, J., 1987. Technology and heterogeneous engineering: The case of Portuguese expansion. *In*: W.E. Bijker, T.P. Hughes, and T.J. Pinch, eds. *The social construction of technological systems: New directions in the sociology and history of technology*. Cambridge, Massachusetts, United States: MIT Press, 111–134.

Layton, E.T., 1974. Technology as knowledge. *Technology and Culture*, 15 (1), 31–41.

Leach, M., Rockström, J., Raskin, P., Scoones, I., Stirling, A., Smith, A., and Thompson, J., 2012. Transforming innovation for sustainability. *Ecology and Society*, 17 (2)

Lee, K. and Lim, C., 2001. Technological regimes, catching-up and leapfrogging: Findings from the Korean industries. *Research Policy*, 30 (3), 459–483.

Lee, K. and Malerba, F., 2017. Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy*, 46 (2), 338–351.

Lee, T.L. and Von Tunzelmann, N., 2005. A dynamic analytic approach to national innovation systems: The IC industry in Taiwan. *Research Policy*, 34 (4), 425–440.

Leite, R.C. de C., Leal, M.R.L.V., Cortez, L.A.B., Griffin, M.W., and Scandiffio, M.I.G., 2009. Can Brazil replace 5% of the 2025 gasoline world demand with ethanol? *Energy*, 34 (5), 655–661.

Lema, R. and Lema, A., 2012. Technology transfer? The rise of China and India in green technology sectors. *Innovation and Development*, 2 (1), 23–44.

Lema, A. and Lema, R., 2013. Technology transfer in the clean development mechanism: Insights from wind power. *Global Environmental Change*, 23 (1), 301–313.

Lema, R., Quadros, R., and Schmitz, H., 2015. Reorganising global value chains and building innovation capabilities in Brazil and India. *Research Policy*, 44 (7), 1376–1386.

van Lente, H., Hekkert, M., Smits, R., and van Waveren, B., 2003. Roles of systemic intermediaries in transition processes. *International Journal of Innovation Management*, 07 (03), 247–279.

Leonard-Barton, D., 1995. *Wellsprings of knowledge: Building and sustaining the sources of innovation*. Cambridge, Massachusetts, United States: Harvard Business School Press.

Levinthal, D.A., 1998. The slow pace of rapid technological change: Gradualism and punctuation in technological change. *Industrial and Corporate Change*, 7 (2), 217–248.

Levinthal, D.A. and March, J.G., 1993. The myopia of learning. *Strategic Management Journal*, 14 (2), 95–112.

Li, Y., Vanhaverbeke, W., and Schoenmakers, W., 2008. Exploration and exploitation in innovation: Reframing the interpretation. *Creativity and Innovation Management*, 17 (2), 107–126.

Lim, Y., 2000. Development of the public sector in the Korean innovation system. *International Journal of Technology Management*, 20 (5–8), 684–701.

Lincoln, Y.S., 1995. Emerging criteria for quality in qualitative and interpretive research. *Qualitative Inquiry*, 1 (3), 275–289.

Lindner, R., Daimer, S., Beckert, B., Heyen, N., Koehler, J., Teufel, B., Warnke, P., and Wydra, S., 2016. *Addressing directionality: Orientation failure and the systems of innovation heuristic. Towards reflexive governance.* Discussion Papers Innovation Systems and Policy Analysis (52). Karlsruhe, Germany: Fraunhofer ISI.

Lindner, S., Alberola, E., Alessi, M., Behrens, A., Clochard, G.-J., Coninck, H.D., and Tuokko, K., 2017. *International R&I collaboration on mitigation*. Working Document Series (5). CARISMA.

List, F., 1841. *The national system of political economy*. Philadelphia, Pennsylvania, United States: J. B. Lippincott & Company.

Liu, J., Chaminade, C., and Asheim, B.T., 2013. The geography and structure of global innovation networks: A knowledge base perspective. *European Planning Studies*, 21 (9), 1456–1473.

Liu, X. and White, S., 2001. Comparing innovation systems: A framework and application to China's transitional context. *Research Policy*, 30 (7), 1091–1114.

Loorbach, D., Frantzeskaki, N., and Avelino, F., 2017. Sustainability transitions research: Transforming science and practice for societal change. *Annual Review of Environment and Resources*, 42 (1), 599–626.

Lopes, M.L., Paulillo, S.C. de L., Godoy, A., Cherubin, R.A., Lorenzi, M.S., Giometti, F.H.C., Bernardino, C.D., de Amorim Neto, H.B., and de Amorim, H.V., 2016. Ethanol production in Brazil: A bridge between science and industry. *Brazilian Journal of Microbiology*, 47 (1), 64–76.

Lorentzen, J., 2009. Learning by firms: The black box of South Africa's innovation system. *Science and Public Policy*, 36 (1), 33–45.

Lorentzen, J., 2010. Learning and innovation: What's different in the (sub) tropics and how do we explain it? A review essay. *Science, Technology & Society*, 14 (1), 177–205.

Lorentzen, J. and Barnes, J., 2004. Learning, upgrading, and innovation in the South African automotive industry. *The European Journal of Development Research*, 16 (3), 465–498.

Lundvall, B.-Å., 1992. *National systems of innovations: Towards a theory of innovation and interactive learning.* London, United Kingdom: Pinter.

Lundvall, B.-Å. and Johnson, B., 1994. The learning economy. *Journal of Industry Studies*, 1 (2), 23–42.

Lundvall, B.-Å., Joseph, K.J., Chaminade, C., and Vang, J., eds., 2009. *Handbook of innovation systems and developing countries: Building domestic capabilities in a global setting*. Cheltenham, United Kingdom: Edward Elgar Publishing.

Lundvall, B.-A., 2007. National innovation systems: Analytical concept and development tool. *Industry & Innovation*, 14 (1), 95–119.

Lundvall, B.-Å., 2016. *The learning economy and the economics of hope*. London, United Kingdom: Anthem Press.

Lundvall, B.-A., 2019. *Transformational innovation policy: Reflections from an innovation system perspective.* Paper presented at the inter-network workshop on 'transformative innovation policy' organised by the Utrecht University on 5-6 February 2019. Utrecht, the Netherlands.

Lynn, L.H., Reddy, N.M., and Aram, J.D., 1996. Linking technology and institutions: The innovation community framework. *Research Policy*, 25 (1), 91–106.

Mackenzie, D. and Spinardi, G., 1995. Tacit knowledge, weapons design, and the uninvention of nuclear weapons. *American Journal of Sociology*, 101 (1), 44–99.

MacKenzie, D. and Wajcman, J., eds., 1999. *The social shaping of technology*. London, United Kingdom: Open University Press.

Malerba, F., 2002. Sectoral systems of innovation and production. *Research Policy*, 31 (2), 247–264.

Manniche, J., 2012. Combinatorial knowledge dynamics: On the usefulness of the differentiated knowledge bases model. *European Planning Studies*, 20 (11), 1823–1841.

Mantel, S.J. and Rosegger, G., 1987. The role of third-parties in the diffusion of innovations: a survey. *In*: R. Rothwell and J. Bessant, eds. *Innovation: Adaptation and growth*. Amsterdam, the Netherlands: Elsevier, 123–134.

March, J.G., 1991. Exploration and exploitation in organizational learning. *Organization Science*, 2 (1), 71–87.

Marengo, L., 1993. Knowledge distribution and coordination in organizations: On some social aspects of the exploitation vs exploration trade-off. *Revue Internationale de Systémique*, 7 (5), 553–571.

Marin, A. and Bell, M., 2010. The local/global integration of MNC subsidiaries and their technological behaviour: Argentina in the late 1990s. *Research Policy*, 39 (7), 919–931.

Marin, A. and Giuliani, E., 2011. MNC subsidiaries' position in global knowledge networks and local spillovers: Evidence from Argentina. *Innovation and Development*, 1 (1), 91–114.

Markard, J., Raven, R., and Truffer, B., 2012. Sustainability transitions: An emerging field of research and its prospects. *Research Policy*, 41 (6), 955–967.

Markard, J. and Truffer, B., 2008. Technological innovation systems and the multi-level perspective: Towards an integrated framework. *Research Policy*, 37 (4), 596–615.

Martin, B.R., 2016. Twenty challenges for innovation studies. *Science and Public Policy*, 43 (3), 432–450.

Martin, R., 2013. Differentiated knowledge bases and the nature of innovation networks. *European Planning Studies*, 21 (9), 1418–1436.

Marxt, C. and Brunner, C., 2013. Analyzing and improving the national innovation system of highly developed countries: The case of Switzerland. *Technological Forecasting and Social Change*, 80 (6), 1035–1049.

Mathews, J., 2009. China, India and Brazil: Tiger technologies, dragon multinationals and the building of national systems of economic learning. *Asian Business & Management*, 8 (1), 5–32.

Mazzucato, M., 2017. *Mission-oriented innovation policy: Challenges and opportunities*. IIPP Working Paper Series (1), London, United Kingdom: Institute for Innovation and Public Purpose.

Mazzucato, M., 2018. Mission-oriented innovation policies: Challenges and opportunities. *Industrial and Corporate Change*, 27 (5), 803–815.

Mazzucato, M., 2019. *A mission-oriented UK industrial strategy*. London, United Kingdom: United Kingdom: Institute for Innovation and Public Purpose.

Mazzucato, M. and Penna, C., 2016. *The Brazilian innovation system: A mission-oriented policy proposal*. Brasilia, Brazil: Centro de Gestão e Estudos Estratégicos.

Mazzucato, M. and Perez, C., 2014. *Innovation as growth policy: The challenge for Europe*. SPRU Working Paper Series (13), Brighton, United Kingdom: SPRU.

McEvily, B. and Zaheer, A., 1999. Bridging ties: A source of firm heterogeneity in competitive capabilities. *Strategic Management Journal*, 20 (12), 1133–1156.

McGrath, R.G., 2001. Exploratory learning, innovative capacity and management oversight. *Academy of Management Journal*, 44 (1), 118–131.

Meadowcroft, J., 2009. What about the politics? Sustainable development, transition management, and long term energy transitions. *Policy Sciences*, 42 (4), 323–340.

Meadows, D.H., Meadows, D.L., and Randers, J., 1972. *The limits to growth: A report for the Club of Rome's project on the predicament of mankind*. New York City, New York, United States: Universe Books.

Meijer, P.C., Verloop, N., and Beijaard, D., 2002. Multi-method triangulation in a qualitative study on teachers' practical knowledge: An attempt to increase internal validity. *Quality and Quantity*, 36 (2), 145–167.

Metcalfe, S., 1995. The economic foundations of technology policy: Equilibrium and evolutionary perspectives. *In*: *Handbook of the economics of innovation and technological change*. London, United Kingdom: Blackwell Publishing, 409–512.

Metcalfe, S. and Ramlogan, R., 2008. Innovation systems and the competitive process in developing economies. *The Quarterly Review of Economics and Finance*, 48 (2), 433–446.

Meuer, J., Rupietta, C., and Backes-Gellner, U., 2015. Layers of co-existing innovation systems. *Research Policy*, 44 (4), 888–910.

Meyer, A.S., Rosgaard, L., and Sørensen, H.R., 2009. The minimal enzyme cocktail concept for biomass processing. *Journal of Cereal Science*, 50 (3), 337–344.

Meyer, K.E., Mudambi, R., and Narula, R., 2011. Multinational enterprises and local contexts: The opportunities and challenges of multiple embeddedness. *Journal of Management Studies*, 48 (2), 235–252.

Meyers, S. and Marquis, D.G., 1969. *Successful industrial innovations*. Washington DC, United States: National Science Foundation.

MI, 2016. Enabling framework for Mission Innovation [online]. Available from: www.mission-innovation.net [Accessed 5 Oct 2018].

MI, 2018. Mission Innovation [online]. Available from: Available from: www.mission-innovation.net [Accessed 5 Oct 2018].

Miettinen, R., 2002. *National innovation system: Scientific concept or political rhetoric*. Helsinki, Finland: Edita.

Miles, M.B. and Huberman, M.A., 1994. *Qualitative data analysis: An expanded sourcebook*. London, United Kingdom: Sage Publications.

Moodysson, J., 2008. Principles and practices of knowledge creation: On the organization of "buzz" and "pipelines" in life science communities. *Economic Geography*, 84 (4), 449–469.

Morrison, A., 2008. Gatekeepers of knowledge within industrial districts: Who they are, how they interact. *Regional Studies*, 42 (6), 817–835.

Morrison, A., Rabellotti, R., and Zirulia, L., 2012. When do global pipelines enhance the fiffusion of knowledge in clusters? *Economic Geography*, 89 (1), 77–96.

Morse, J.M., Barrett, M., Mayan, M., Olson, K., and Spiers, J., 2002. Verification strategies for establishing reliability and validity in qualitative research. *International Journal of Qualitative Methods*, 1 (2), 13–22.

Mosley, L., 2012. *Interview research in political science*. London, United Kingdom: Cornell University Press.

Motohashi, K., 2005. University–industry collaborations in Japan: The role of new technology-based firms in transforming the national innovation system. *Research Policy*, 34 (5), 583–594.

Motohashi, K. and Yun, X., 2007. China's innovation system reform and growing industry and science linkages. *Research Policy*, 36 (8), 1251–1260.

Mowery, D.C., 1998. The changing structure of the US national innovation system: Implications for international conflict and cooperation in R&D policy. *Research Policy*, 27 (6), 639–654.

Mowery, D.C., Nelson, R.R., and Martin, B.R., 2010. Technology policy and global warming: Why new policy models are needed (or why putting new wine in old bottles won't work). *Research Policy*, 39 (8), 1011–1023.

Mowery, D.C. and Oxley, J.E., 1995. Inward technology transfer and competitiveness: The role of national innovation systems. *Cambridge Journal of Economics*, 19 (1), 67–93.

Mowery, D.C. and Rosenberg, N., 1979. The influence of market demand upon innovation: A critical review of some recent empirical studies. *Research Policy*, 8, 102–153.

Muller, E. and Zenker, A., 2001. Business services as actors of knowledge transformation: The role of KIBS in regional and national innovation systems. *Research Policy*, 30 (9), 1501–1516.

Mytelka, L.K. and Smith, K., 2002. Policy learning and innovation theory: An interactive and co-evolving process. *Research Policy*, 31 (8–9), 1467–1479.

Narula, R. and Zanfei, A., 2004. Globalisation of innovation: The role of multinational enterprises. In: J. Fagerberg, D.C. Mowery, and R.R. Nelson, eds. *The Oxford handbook of innovation*. London, United Kingdom: Oxford University Press, 318–345.

Nelson, R.R., 1974. Intellectualizing about the moon-ghetto metaphor: A study of the current malaise of rational analysis of social problems. *Policy Sciences*, 5 (4), 375–414.

Nelson, R.R., 1993. *National innovation systems: A comparative analysis*. London, United Kingdom: Oxford University Press.

Nelson, R.R., 2004. The market economy, and the scientific commons. *Research Policy*, 33 (3), 455–471.

Nelson, R.R., 2011. Economic development as an evolutionary process. *Innovation and Development*, 1 (1), 39–49.

Nelson, R.R., 2012. The moon and the ghetto revisited. *Science and Public Policy*, 38 (9), 681–690.

Nelson, R.R. and Winter, S.G., 1977. In search of useful theory of innovation. *Research Policy*, 6 (1), 36–76.

Nelson, R.R. and Winter, S.G., 1982. *An evolutionary theory of economic change*. Cambridge, Massachusetts, United States: Belknap Press.

Nightingale, P., 1998. A cognitive model of innovation. *Research Policy*, 27 (7), 689–709.

Nilsson, M., Griggs, D., and Visbeck, M., 2016. Policy: Map the interactions between sustainable development goals. *Nature*, 534 (7606), 320–322.

Niosi, J., 2002. National systems of innovations are "x-efficient" (and x-effective): Why some are slow learners. *Research Policy*, 31 (2), 291–302.

Nonaka, I. and Takeuchi, H., 1995. *The knowledge-creating company*. London, United Kingdom: Oxford University Press.

North, D.C., 1991. Institutions. *The Journal of Economic Perspectives*, 5 (1), 97–112.

Novozymes, 2007. Novozymes concludes agreement in Brazil on the development of second-generation biofuels [online]. *Newsletter*. Available from: www.novozymes.com [Accessed 5 Oct 2018].

Novozymes, 2009. Novozymes among the 100 best companies to work for in Brazil [online]. *Newsletter*. Available from: www.novozymes.com [Accessed 5 Oct 2018].

Novozymes, 2010. Novozymes' IT solution sets new standards in the bio-industry [online]. *Newsletter*. Available from: www.novozymes.com [Accessed 5 Oct 2018].

Novozymes, 2011. Novozymes inaugurates R&D laboratories in Brazil [online]. *Newsletter*. Available from: www.novozymes.com [Accessed 5 Oct 2018].

Novozymes, 2012. *Novozymes Cellic® CTec3 - Secure your plant's lowest total cost*. Copenhagen, Denmark: Novozymes.

Novozymes, 2015. Partnering for impact. Novozymes launches new purpose statement, strategy, and long-term targets [online]. *Newsletter*. Available from: www.novozymes.com [Accessed 5 Oct 2018].

Novozymes, 2016. Sustainability: Well positioned to deliver on global goals [online]. Available from: www.novozymes.com [Accessed 1 May 2019].

Novozymes, 2017. *The Novozymes report 2017*. Copenhagen, Denmark: Novozymes.

Nunes, S. and Lopes, R., 2015. Firm performance, innovation modes and territorial embeddedness. *European Planning Studies*, 23 (9), 1796–1826.

Ockwell, D. and Byrne, R., 2016. Improving technology transfer through national systems of innovation: Climate relevant innovation-system builders (CRIBs). *Climate Policy*, 16 (7), 836–854.

Ockwell, D.G., Haum, R., Mallett, A., and Watson, J., 2010. Intellectual property rights and low carbon technology transfer: Conflicting discourses of diffusion and development. *Global Environmental Change*, 20 (4), 729–738.

Ockwell, D.G. and Mallett, A., eds., 2012. *Low-carbon technology transfer: From rhetoric to reality*. London, United Kingdom: Earthscan.

Ockwell, D.G., Sagar, A.D., and de Coninck, H., 2014. Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: Towards a needs driven approach. *Climatic Change*, 41 (3), 401–415.

Ockwell, D.G., Watson, J., MacKerron, G., Pal, P., and Yamin, F., 2008. Key policy considerations for facilitating low carbon technology transfer to developing countries. *Energy Policy*, 36 (11), 4104–4115.

OECD, 1997. *National innovation systems*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2002. *Dynamising national innovation systems*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2005. *Oslo manual: The measurement of scientific and technological activities*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2008. *Open innovation in global networks*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2012. International Energy Agency Implementing Agreements. *In*: *Meeting global challenges through better governance: international co-operation in science, technology and innovation*. Paris, France: Organisation for Economic Co-operation and Development, 131–150.

OECD, 2014. *Frascati manual: Guidelines for collecting and reporting data on research and experimental development*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2015. *System innovation: Synthesis report*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2016. *OECD Reviews of Innovation Policy: Sweden 2016*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2017. *OECD Reviews of Innovation Policy: Norway 2017*. Paris, France: Organisation for Economic Co-operation and Development.

OECD, 2018. *OECD Reviews of Innovation Policy: Finland 2018*. Paris, France: Organisation for Economic Co-operation and Development.

Oldham, G., 2006. Science and technology advice within the United Nations: Some lessons from past experience. *Science and Public Policy*, 33 (9), 647–651.

Owen-Smith, J., Riccaboni, M., Pammolli, F., and Powell, W.W., 2002. A comparison of U.S. and European university-industry relations in the life sciences. *Management Science*, 48 (1), 24–43.

Owen, R., Macnaghten, P., and Stilgoe, J., 2012. Responsible research and innovation: From science in society to science for society, with society. *Science and Public Policy*, 39 (6), 751–760.

Parayil, G., 2005. From "Silicon Island" to "Biopolis of Asia": Innovation policy and shifting competitive strategy in Singapore. *California Management Review*, 47 (2), 50–73.

Parthasarathy, B. and Aoyama, Y., 2006. From software services to R&D Services: Local entrepreneurship in the software industry in Bangalore, India. *Environment and planning A: Economy and Space*, 38 (7), 1269–1285.

Patel, P. and Pavitt, K., 1994. National innovation systems: Why they are important, and how they might be measured and compared. *Economics of Innovation and New Technology*, 3 (1), 77–95.

Patton, M.Q., 1990. *Qualitative evaluation and research methods*. London, United Kingdom: Sage Publications.

Perez, C., 1983. Structural change and assimilation of new technologies in the economic and social systems. *Futures*, 15 (4), 357–375.

Pietrobelli, C. and Rabellotti, R., 2011. Global value chains meet innovation systems: Are there learning opportunities for developing countries? *World Development*, 39 (7), 1261–1269.

Pinch, T.J. and Bijker, W.E., 1984. The social construction of facts and artefacts: Or how the sociology of science and the sociology of technology might benefit each other. *Social Studies of Science*, 14 (3), 399–441.

Pinto, H. and Santos Pereira, T., 2013. Efficiency of innovation systems in Europe: An institutional approach to the diversity of national profiles. *European Planning Studies*, 21 (6), 755–779.

Polizeli, M.L.T.., Somera, A.F., Lucas, R.C., Nozawa, M.S.F., and Michelin, M., 2017. Enzymes involved in the biodegradation of sugarcane biomass: Challenges and perspectives. *In*: M.S. Buckeridge and A.P. Souza, eds. *Advances of basic science for second generation bioethanol from sugarcane*. London, United Kingdom: Springer, 55–79.

Popp, A., 2000. Swamped in information but starved of data: Information and intermediaries in clothing supply chains. *Supply Chain Management*, 5 (3), 151–161.

Porter, M.E., 1990. *Competitive advantage of nations*. New York City, New York, United States: Free Press.

Powell, W.W., Koput, K.W., and Smith-Doerr, L., 1996. Interorganizational collaboration and the locus of innovation: Networks of learning in biotechnology. *Administrative Science Quarterly*, 41 (1), 116–145.

Rai, V., Schultz, K., and Funkhouser, E., 2014. International low carbon technology transfer: Do intellectual property regimes matter? *Global Environmental Change*, 24, 60–74.

Rakas, M. and Hain, D.S., 2019. The state of innovation system research: What happens beneath the surface? *Research Policy*.

Randalls, S., 2010. History of the 2°C climate target. *Wiley Interdisciplinary Reviews: Climate Change*, 1 (4), 598–605.

Raven, R., 2005. *Strategic Niche Management for Biomass: A comparative study on the experimental introduction of bioenergy technologies in the Netherlands and Denmark*. Eindhoven, the Netherlands: Eindhoven University of Technology.

Ray, G.F., 1989. Full circle: The diffusion of technology. *Research Policy*, 18 (1), 1–18.

Rennings, K., 2000. Redefining innovation: Eco-innovation research and the contribution from ecological economics. *Ecological economics*, 32 (2), 319–332.

Rip, A., 1997. A cognitive approach to relevance of science. *Social Science Information*, 36 (4), 615–640.

Rip, A. and Kemp, R., 1998. Technological change. *In*: S. Rayner and E.L. Malone, eds. *Human choice and climate change*. Columbus, Ohio, United States: Battelle Press, 327–399.

Rodríguez-Pose, A. and Crescenzi, R., 2008. Research and development, spillovers, innovation systems, and the genesis of regional growth in Europe. *Regional Studies*, 42 (1), 51–67.

Røpke, I., 2012. The unsustainable directionality of innovation: The example of the broadband transition. *Research Policy*, 41 (9), 1631–1642.

Rosenberg, N., 1969. The direction of technological change: Inducement mechanisms and focusing devices. *Economic Development and Cultural Change*, 18 (1), 1–24.

Rothwell, R., 1992. Successful industrial innovation: Critical factors for the 1990s. *R&D Management*, 22 (3), 221–240.

Rotmans, J., Kemp, R., and Asselt, M. V., 2001. More evolution than revolution: Transition management in public policy. *Foresight*, 3 (1), 15–31.

Ruiz, E., Cara, C., Manzanares, P., Ballesteros, M., and Castro, E., 2008. Evaluation of steam explosion pre-treatment for enzymatic hydrolysis of sunflower stalks. *Enzyme and Microbial Technology*, 42 (2), 160–166.

Saad, M. and Zawdie, G., 2005. From technology transfer to the emergence of a triple helix culture: The experience of Algeria in innovation and technological capability development. *Technology Analysis & Strategic Management*, 17 (1), 89–103.

Sagar, A., 2010. *Climate innovation centres: Technology co-operation to meet climate challenges*. London, United Kingdom: Climate Strategies.

Sagar, A.D., 2011. *Climate innovation centres: A new way to foster climate technologies in the developing world?* Washington DC, United States: World Bank.

Sagar, A.D., Bremner, C., and Grubb, M., 2009. Climate innovation centres: A partnership approach to meeting energy and climate challenges. *Natural Resources Forum*, 33 (4), 274–284.

Saldana, J., 2009. *The coding manual for qualitative researchers*. London, United Kingdom: Sage Publications.

Salles-Filho, S.L.M., Castro, P.F.D. de, Bin, A., Edquist, C., Ferro, A.F.P., and Corder, S., 2017. Perspectives for the Brazilian bioethanol sector: The innovation driver. *Energy Policy*, 108, 70–77.

Sánchez, Ó.J. and Cardona, C.A., 2008. Trends in biotechnological production of fuel ethanol from different feedstocks. *Bioresource Technology*, 99 (13), 5270–5295.

Sarantakos, S., 2005. *Social research*. London, United Kingdom: Red Globe Press.

Saunders, M., Thornhill, A., and Lewis, P., 2009. *Research methods for business students*. London, United Kingdom: Pearson Publishing.

Sayer, A., 2000. *Realism and social science*. London, United Kingdom: Sage.

Schlaile, M., Urmetzer, S., Blok, V., Andersen, A., Timmermans, J., Mueller, M., Fagerberg, J., and Pyka, A., 2017. Innovation systems for transformations towards sustainability? Taking the normative dimension seriously. *Sustainability*, 9 (12), 2253.

Schot, J., Boni, A., Ramirez, M., and Steward, F., 2018. *Addressing the sustainable development goals through transformative innovation policy*. TIPC Research Brief (1), Brighton, United Kingdom: Transformative Innovation Policy Consortium.

Schot, J. and Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy. *Technology Analysis & Strategic Management*, 20 (5), 537–554.

Schot, J. and Steinmueller, E.W., 2018. Three frames for innovation policy: R&D, systems of innovation and transformative change. *Research Policy*, 47 (9), 1554–1567.

Schumpeter, J., 1942. *Capitalism, socialism and democracy*. London, United Kingdom: Routledge.

Seale, C., 1999. Quality in qualitative research. *Qualitative Inquiry*, 5 (4), 465–478.

Sharif, N., 2006. Emergence and development of the national innovation systems concept. *Research Policy*, 35 (5), 745–766.

Sharma, P., Nookala, S.B.S., and Sharma, A., 2012. India's national and regional innovation systems: Challenges, opportunities and recommendations for policy makers. *Industry & Innovation*, 19 (6), 517–537.

Shove, E. and Walker, G., 2007. Caution! Transitions ahead: Politics, practice, and sustainable transition management. *Environment and Planning*, 39 (4), 763–770.

Siggelkow, N. and Levinthal, D.A., 2003. Temporarily divide to conquer: Centralized, decentralized, and reintegrated organizational approaches to exploration and adaptation. *Organization Science*, 14 (6), 650–669.

Silverman, D., 2013. *Doing qualitative research*. London, United Kingdom: Sage Publications.

Smith, A. and Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. *Research Policy*, 41 (6), 1025–1036.

Smith, A. and Stirling, A., 2007. Moving outside or inside? Objectification and reflexivity in the governance of socio-technical systems. *Journal of Environmental Policy & Planning*, 9 (3–4), 351–373.

Smith, A., Stirling, A., and Berkhout, F., 2005. The governance of sustainable socio-technical transitions. *Research Policy*, 34 (10), 1491–1510.

Smith, A., Voß, J.-P., and Grin, J., 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. *Research Policy*, 39 (4), 435–448.

Smith, J.B., Schneider, S.H., Oppenheimer, M., Yohe, G.W., Hare, W., Mastrandrea, M.D., Patwardhan, A., Burton, I., Corfee-Morlot, J., Magadza, C.H.D., Füssel, H.-M., Pittock, B.A., Rahman, A., Suarez, A., and van Ypersele, J.-P., 2009. Assessing dangerous climate change through an update of the Intergovernmental Panel on Climate Change (IPCC) 'reasons for concern'. *Proceedings of the National Academy of Sciences of the United States of America*, 106 (11), 4133–7.

Smith, K., 1994. *Interactions in knowledge systems: Foundations, policy implications and empirical methods*. STEP Report Series (10), Oslo, Norway.

Smith, K., 2000. Innovation as a systemic phenomenon: Rethinking the role of policy. *Enterprise and Innovation Management Studies*, 1 (1), 73–102.

Smith, K., 2017. Innovation policy for the global commons: Multilateral collaboration and polycentric governance in a heteropolar world. *Oxford Review of Economic Policy*, 33 (1), 49–65.

Smith, M.R. and Marx, L., eds., 1994. *Does technology drive history? The dilemma of technological determinism*. Cambridge, Massachusetts, United States: MIT Press.

Smits, R.E., Kuhlmann, S., and Shapira, P., eds., 2010. *The theory and practice of innovation policy: An international research handbook*. London, United Kingdom: Edward Elgar Publishing.

Soccol, C.R., Vandenberghe, L.P. de S., Medeiros, A.B.P., Karp, S.G., Buckeridge, M., Ramos, L.P., Pitarelo, A.P., Ferreira-Leitão, V., Gottschalk, L.M.F., Ferrara, M.A., Silva Bon, E.P. da, Moraes, L.M.P. de, Araújo, J. de A., and Torres, F.A.G., 2010. Bioethanol from lignocelluloses: Status and perspectives in Brazil. *Bioresource Technology*, 101 (13), 4820–4825.

Soccol, C.R., Vandenberghe, L.P.S., Costa, B., Woiciechowski, A.L., de Carvalho, J.C., Medeiros, A.B.P., Francisco, A.M., and Bonomi, L.J., 2005. Brazilian biofuel program: An overview. *Journal of Scientific and Industrial Research*, 64 (11), 897–904.

Soete, L., 2013. Is Innovation always good? *In*: J. Fagerberg, E.S. Andersen, and B. Martin, eds. *Innovation studies: Evolution and future challenges*. London, United Kingdom: Oxford University Press, 134–144.

Soete, L., Verspagen, B., and ter Weel, B., 2010. Systems of innovation. *In*: B.H. Hall, and N. Rosenberg, eds. *Handbook of the economics of innovation*. London, United Kingdom: Elsevier, 1159–1180.

Solleiro, J.L. and Castañón, R., 2005. Competitiveness and innovation systems: The challenges for Mexico's insertion in the global context. *Technovation*, 25 (9), 1059–1070.

Souza, A.P., Grandis, A., Leite, D.C.C., and Buckeridge, M.S., 2014. Sugarcane as a bioenergy source: History, performance, and perspectives for second-generation bioethanol. *Bioenergy Research*, 7 (1), 24–35.

Souza, L.G.A., Moraes, M.A.F.D., Poz, M.E.S.D., and Silveira, J.M.F.J., 2015. Collaborative networks as a measure of the innovation systems in second-generation ethanol. *Scientometrics*, 103 (2), 355–372.

Sovacool, B.K. and Hess, D.J., 2017. Ordering theories: Typologies and conceptual frameworks for sociotechnical change. *Social Studies of Science*, 47 (5), 703–750.

Spencer, J.W., 2003. Firms' knowledge-sharing strategies in the global innovation system: Empirical evidence from the flat panel display industry. *Strategic Management Journal*, 24 (3), 217–233.

Standke, K.-H., 2006. Sixty years of UN and UNESCO: Science and technology in global cooperation, the case of the United Nations and UNESCO. *Science and Public Policy*, 33 (9), 627–646.

Stankiewicz, R., 1992. Technology as an autonomous socio-cognitive system. *In*: Hariolf Grupp, ed. *Dynamics of science-based innovation*. Berlin, Germany: Springer, 19–44.

Stankiewicz, R., 1995. The role of the science and technology infrastructure in the development and diffusion of industrial automation in Sweden. *In*: B. Carlsson, ed. *Technological systems and economic performance: The case of factory automation*. London, United Kingdom: Springer, 165–210.

Stankiewicz, R., 2000. The concept of 'design space'. *In*: J. Ziman, ed. *Technological innovation as an evolutionary process*. London, United Kingdom: Cambridge University Press, 234–247.

Steffen, W., Richardson, K., Rockström, J., Cornell, S., Fetzer, I., Bennett, E., Biggs, R., Carpenter, S.R., de Wit, C.A., Folke, C., Mace, G., Persson, L.M., Veerabhadran, R., Reyers, B., and Sörlin, S., 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347 (6223).

Stern, N., 2007. *The economics of climate change: The Stern review*. London, United Kingdom: Cambridge University Press.

Sternberg, R. and Arndt, O., 2009. The firm or the region: What determines the innovation behavior of European firms? *Economic Geography*, 77 (4), 364–382.

Steward, F., 2008. *Breaking the boundaries: Transformative innovation for the global good*. London, United Kingdom: NESTA

Steward, F., 2012. Transformative innovation policy to meet the challenge of climate change: Sociotechnical networks aligned with consumption and end-use as new transition arenas for a low-carbon society or green economy. *Technology Analysis & Strategic Management*, 24 (4), 331–343.

Stewart, J. and Hyysalo, S., 2008. Intermediaries, users and social learning in technological innovation. *International Journal of Innovation Management*, 12 (3), 295–325.

Stirling, A., 2008. 'Opening up' and 'closing down': Power, participation, and pluralism in the social appraisal of technology. *Science, Technology, & Human Values*, 33 (2), 262–294.

Stirling, A., 2014. *Emancipating transformations: From controlling 'the transition' to culturing plural radical progress*. STEPS Working Paper (64). Brighton, United Kingdom: STEPS Centre.

Stirling, A., 2015. *Towards innovation democracy? Participation, responsibility and precaution in innovation governance*. STEPS Working Paper (78). Brighton, United Kingdom: STEPS Centre.

Strauss, A. and Corbin, J., 1990. *Basics of qualitative research: Grounded theory procedures and techniques*. London, United Kingdom: Sage Publications.

Sutton, J., 2012. *Competing in capabilities: The globalization process*. London, United Kingdom: Oxford University Press.

Sutz, J., 2019. *Innovation policy as an inclusive strategy*. Presentation given at the conference on 'The new role of the state for the emergence and diffusion of innovation' organised by the Volkswagen Foundation on 20-22 February 2019. Hanover, Germany.

Suzigan, W. and Albuquerque, E. da M. e, 2011. The underestimated role of universities for the Brazilian system of innovation. *Revista de Economia Política*, 31 (1), 3–30.

Tang, M. and Hussler, C., 2011. Betting on indigenous innovation or relying on FDI: The Chinese strategy for catching-up. *Technology in Society*, 33 (1–2), 23–35.

TEC, 2015. *Strengthening national systems of innovation to enhance action on climate change*. Bonn, Germany: Technology Executive Committee.

TEC, 2016. *Technology and the UNFCCC: Building the foundation for sustainable development*. Bonn, Germany: Technology Executive Committee.

TEC, 2017. *Technological innovation for the Paris agreement: Implementing nationally determined contributions, national adaptations plans and mid-century strategies*. Bonn, Germany: Technology Executive Committee.

Teixeira, A.A.C., 2014. Evolution, roots and influence of the literature on national systems of innovation: A bibliometric account. *Cambridge Journal of Economics*, 38 (1), 181–214.

TIPC, 2019. Inter-network dialogue on transformative innovation policy agrees research agenda [online]. Available from: www.tipconsortium.net [Accessed 1 May 2019].

Timmermans, S. and Tavory, I., 2012. Theory construction in qualitative research: From grounded theory to abductive analysis. *Sociological Theory*, 30 (3), 167–186.

Tokatliy, N., 2015. Single-firm case studies in economic geography: Some methodological reflections on the case of Zara. *Journal of Economic Geography,* 15 (3), 631–647.

Torrens, J. and Schot, J., 2017. *The roles of experimentation in transformative innovation policy*. TIPC Research Brief (2), Brighton, United Kingdom: Transformative Innovation Policy Consortium.

Torres-Fuchslocher, C., 2010. Understanding the development of technology-intensive suppliers in resource-based developing economies. *Research Policy*, 39 (2), 268–277.

Trindade, S.C., 2009. The sustainability of biofuels depends on international trade. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 31 (18), 1680–1686.

Trochim, W.M.K., 2002. *Research methods knowledge base*. New York City, New York, United States: Atomic Dog Publishing.

Truffer, B., 2015. Challenges for technological innovation systems research: Introduction to a debate. *Environmental Innovation and Societal Transitions*, 16, 65–66.

Truffer, B. and Battistini, B., 2015. *Global innovation systems and sustainability transitions: Towards a transnational perspective*. ESS Working Paper Series, Dübendorf, Switzerland: Eawag.

Tsai, F.-S., Hsieh, L.H.Y., Fang, S.-C., and Lin, J.L., 2009. The co-evolution of business incubation and national innovation systems in Taiwan. *Technological Forecasting and Social Change*, 76 (5), 629–643.

Turnheim, B. and Geels, F.W., 2012. Regime destabilisation as the flipside of energy transitions: Lessons from the history of the British coal industry (1913-1997). *Energy Policy*, 50, 35–49.

Turnheim, B., Kivimaa, P., and Berkhout, F., eds., 2018. *Innovating climate governance: Moving beyond experiments*. London, United Kingdom: Cambridge University Press.

UN, 1992. *Agenda 21: Programme of action for sustainable development: Rio declaration on environment and development*. Rio de Janeiro, Brazil: United Nations.

UN, 2000. *United Nations Millennium Declaration*. New York City, New York, United States: United Nations.

UN, 2012. The future we want: A/RES/66/288 [online]. Available from: www.un.org [Accessed 15 November 2018].

UN, 2013. Implementation of agenda 21, the programme for the further implementation of agenda 21 and the outcomes of the world summit on sustainable development and of the United Nations conference on sustainable development: A/RES/67/203 [online]. Available from: www.un.org [Accessed 15 November 2018].

UN, 2014. The road to dignity by 2030: Ending poverty, transforming all lives and protecting the planet; synthesis report of the secretary-general on the post-2015 agenda: A/69/700 [online]. Available from: www.un.org [Accessed 15 November 2018].

UN, 2015. Transforming our world - the 2030 agenda for sustainable development: A/RES/70/1 [online]. Available from: www.un.org [Accessed 15 November 2018].

UN, 2019. Sustainable development goals [online]. Available from: www.sustainabledevelopment.un.org [Accessed 15 November 2018].

UNCTAD, 2011. *A framework for science, technology and innovation policy reviews: Helping countries leverage knowledge and innovation for development*. Geneva, Switzerland: United Nations Conference on Trade and Development.

UNCTAD, 2018. Effectively harnessing science, technology, and innovation to achieve the sustainable development goals: TD/B/C.II/MEM.4/1 [online]. Available from: www.unctad.org [Accessed 15 November 2018].

UNCTAD, 2019. *A framework for science, technology and innovation policy reviews: Harnessing innovation for sustainable development*. Geneva, Switzerland: United Nations Conference on Trade and Development.

UNEP, 2018. *Emissions gap report 2018*. Nairobi, Kenya: United Nations Environment Programme.

UNFCCC, 1992. Report of the intergovernmental negotiating committee for a framework convention on climate change on the work of the second part of its fifth session, held at New York from 30 April to 9 May 1992. Addendum: A/AC.237/18 (Part II)/Add.1 [online]. Available from: www.unfccc.int [Accessed 26 August 2018].

UNFCCC, 1997. Kyoto protocol to the United Nations framework convention on climate change: FCCC/CP/1997/CRP.6 [online]. Available from: www.unfccc.int [Accessed 26 August 2018].

UNFCCC, 2010. Report of the conference of the parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Addendum. Part two: Action taken by the conference of the parties at its sixteenth session: FCCC/CP/2010/7/Add.1 [online]. Available from: www.unfccc.int [Accessed 26 August 2018].

UNFCCC, 2011. Report of the conference of the parties on its seventeenth session, held in Durban from 28 November to 11 December 2011. Addendum. Part two: Action taken by the conference of the parties at its seventeenth session: FCCC/CP/2011/9/Add.1 [online]. Available from: www.unfccc.int [Accessed 26 August 2018].

UNFCCC, 2013. Report of the conference of the parties on its nineteenth session, held in Warsaw from 11 to 23 November 2013. Addendum. Part two: Action taken by the conference of the parties at its nineteenth session: FCCC/CP/2013/10/Add.3 [online]. Available from: www.unfccc.int [Accessed 26 August 2018].

UNFCCC, 2015. Adoption of the Paris agreement: FCCC/CP/2015/L.9/Rev.1 [online]. Available from: www.undocs.org [Accessed 26 August 2018].

UNFCCC, 2016. *Mapping climate technology development and transfer activities and initiatives under and outside the convention relevant to the implementation of the Paris agreement*. Bonn, Germany: United Nations Framework Convention on Climate Change.

UNICA, 2017. Statistics of the sugarcane sector - 2015 [online]. Available from: http://www.unicadata.com.br/ [Accessed 29 Jul 2017].

Verbong, G., Christiaens, W., Raven, R., and Balkema, A., 2010. Strategic niche management in an unstable regime: Biomass gasification in India. *Environmental Science & Policy*, 13 (4), 272–281.

Vincenti, W.G., 1990. *What engineers know and how they know it: Analytical studies from aeronautical history*. Baltimore, Maryland, United States: John Hopkins 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. *Technological Forecasting and Social Change*, 69 (7), 653–680.

Voß, J.-P., Bauknecht, D., and Kemp, R., eds., 2006. *Reflexive governance for sustainable development*. London, United Kingdom: Edward Elgar Publishing.

Wang, Y., Vanhaverbeke, W., and Roijakkers, N., 2012. Exploring the impact of open innovation on national systems of innovation: A theoretical analysis. *Technological Forecasting and Social Change*, 79 (3), 419–428.

Watkins, A., Papaioannou, T., Mugwagwa, J., and Kale, D., 2015. National innovation systems and the intermediary role of industry associations in building institutional capacities for innovation in developing countries: A critical review of the literature. *Research Policy*, 44 (8), 1407–1418.

Watson, J., Byrne, R., Ockwell, D., and Stua, M., 2014. Lessons from China: Building technological capabilities for low carbon technology transfer and development. *Climatic Change*, 131 (3), 387–399.

Watson, J. and Sauter, R., 2011. Sustainable innovation through leapfrogging: A review of the evidence. *International Journal of Technology and Globalisation*, 5 (3/4), 170.

Weber, M.K. and Truffer, B., 2017. Moving innovation systems research to the next level: Towards an integrative agenda. *Oxford Review of Economic Policy*, 33 (1), 101–121.

Weber, M.K. and Hoogma, R., 1998. Beyond national and technological styles of innovation diffusion: A dynamic perspective on cases from the energy and transport sectors. *Technology Analysis & Strategic Management*, 10 (4), 545–566.

Weber, M.K. and Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change. *Research Policy*, 41 (6), 1037–1047.

Wieczorek, A.J. and Hekkert, M.P., 2012. Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and Public Policy*, 39 (1), 74–87.

Wieczorek, A.J., Raven, R., and Berkhout, F., 2015. Transnational linkages in sustainability experiments: A typology and the case of solar photovoltaic energy in India. *Environmental Innovation and Societal Transitions*, 17, 149–165.

Wieczorek, A.J., 2018. Sustainability transitions in developing countries: Major insights and their implications for research and policy. *Environmental Science & Policy*, 84, 204–216.

Winch, G.M. and Courtney, R., 2007. The organization of innovation brokers: An international review. *Technology Analysis and Strategic Management*, 19 (6), 747–763.

Wong, P.-K., 1999. *National innovation systems for rapid technological catch-up: An analytical framework and a comparative analysis of Korea, Taiwan and Singapore*. Paper presented at the conference on 'National innovation systems, industrial dynamics and innovation policy' organised by the DRUID on 9-12 June 1999. Copenhagen, Denmark.

Wong, P.-K., 2003. From using to creating technology: The evolution of Singapore's national innovation system and the changing role of public policy. *In*: S. Lall, and S. Urata, eds. *Competitiveness, FDI and technological activity in East Asia. London*, United Kingdom: Edward Elgar Publishing, 191–238.

Wonglimpiyarat, J., 2010. Commercialization strategies of technology: Lessons from Silicon Valley. *The Journal of Technology Transfer*, 35 (2), 225–236.

World Bank, 2010. *World development report 2010: Development and climate change*. Washington DC, United States: World Bank.

World Bank, 2016. World Bank group launches climate business innovation network [online]. Available from: www.worldbank.org [Accessed 5 Feb 2019].

World Bank, 2018. InfoDev [online]. Available from: www.infodev.org [Accessed 5 Feb 2019].

Wu, W., 2007. Cultivating research universities and industrial linkages in China: The case of Shanghai. *World Development*, 35 (6), 1075–1093.

Xiwei, Z. and Xiangdong, Y., 2007. Science and technology policy reform and its impact on China's national innovation system. *Technology in Society*, 29 (3), 317–325.

Yim, D.S. and Kim, W.D., 2005. The evolutionary responses of Korean government research institutes in a changing national innovation system. *Science, Technology and Society*, 10 (1), 31–55.

Yin, R.K., 2018. *Case study research and applications: Design and methods*. London, United Kingdom: Sage Publications.

Yu, Y.-S., 2016. *Uncovering the cost of cellulosic ethanol production*. Singapore: Lux Research.

Zollo, M., Reuer, J.J., and Singh, H., 2002. Interorganizational routines and performance in strategic alliances. *Organization Science*, 13 (6), 701–713.

Zou, Y. and Zhao, W., 2014. Anatomy of Tsinghua University science park in China: Institutional evolution and assessment. *The Journal of Technology Transfer*, 39 (5), 663–674.